BASEMENT-COVER RELATIONSHIPS AND DEFORMATION IN THE NORTHERN PARAGUAI BELT, CENTRAL BRAZIL: IMPLICATIONS FOR THE NEOPROTEROZOIC-EARLY PALAEOZOIC HISTORY OF WESTERN GONDWANA

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ABSTRACT

The Northern Paraguai Belt, at the SE border of the Amazonian Craton, central Brazil, has been interpreted as a Brasiliano/Pan-African (ca. 650-600 Ma) belt with a foreland basin, recording collisional polyphase tectonism and greenschist facies metamorphism extending from the late Precambrian to the Cambrian-Ordovician. New structural investigations indicate that the older metasedimentary rocks of the Cuiabá Group represent a Tonian-Cryogenian basement assemblage deformed in two contemporaneous fault-bounded structural sub-domains of wrench- (rake<10º) and contraction- (rake~30-40º) dominated sinistral transpression, with tectonic vergence towards the SE. The younger late-Cryogenian to early-Cambrian sedimentary rocks lying to the NW of the Cuiabá Group are non-metamorphic and display only pervasive brittle transtension characterized by normal-oblique faults, fractures and forced drag folds with no consistent vergence pattern. Our analyses suggest that an unconformity separates the metasedimentary Cuiabá Group basement of the Northern Paraguai Belt from the unmetamorphosed sedimentary cover. It is proposed that the latter units were deposited during a post-glacial marine transgression (after ca. 635 Ma) in a post-collisional basin. The Paraguai Belt basement and its post-collisional sedimentary cover share a number of significant geological similarities with sequences in the Bassarides Belt and Taoudéni Basin in the SW portion of the West African Craton.

Keywords: WESTERN GONDWANA; BRASILIANO/PAN-AFRICAN OROGENY; AMAZONIAN CRATON; NORTHERN PARAGUAI BELT.

The rifting and breakup of Rodinia during the Mesoproterozoic to early Neoproterozoic were associated with the deposition of thick marine siliciclastic rocks along newly formed continental margins, as observed in the Northern Paraguai Belt along the southern border of the Amazonian Craton, central Brazil (Tokashiki & Saes 2008). Later, during the assembly of Gondwana and closure of the Pharusian-Goiás ocean (ca. 660-650 Ma), these rocks were deformed and underwent low grade metamorphism (Alvarenga & Trompette 1993; Cordani *et al*. 2013). Evidence for this continental collisional event is well preserved in both the South American and African continents (Almeida 1984; Trompette 1994; Trindade *et al*. 2006; Tohver *et al*. 2006, 2010; Nogueira *et al*. 2007; Alvarenga *et al*. 2012; Bandeira *et al*. 2012; Cordani *et al*. 2013; McGee *et al*. 2015; Merdith *et al*. 2017).

In South America, the deformed Tonian-Cryogenian rocks of the Northern Paraguai fold-thrust belt are known also to be associated with late-Cryogenian to Early Cambrian rocks that outcrop in the southern region of the Amazonian Craton; these have been previously interpreted as being part of a related foreland basin sequence (Alvarenga *et al*. 2012; McGee *et al.* 2014, 2015; Fig. 1).

In the Northern Paraguai Belt, the tectonic deformation of both metasedimentary and adjacent supposedly foreland sedimentary successions are interpreted by Almeida (1964a,b; 1984), Luz *et al*. (1980), Alvarenga & Trompette (1993), Costa *et al*. (2015) and Vasconcelos *et al*. (2015) to be a result of polyphase tectonism. At least four deformation phases, marked by sets of thrust-faults, folds and cleavages, are recognized and related to the long-term collisional history of this orogen that contributed to the assembly of Gondwana at this time (e.g. Alvarenga & Trompette 1993). Importantly, there is no evidence of metamorphism in the younger sedimentary rocks of the supposed foreland basin sequence since organic matter is preserved as a common rock component (Nogueira & Riccomini 2006; Brelaz 2012; Milhomem Neto *et al*. 2013).

The present study brings new field data and structural interpretations concerning the regional setting and significance of the rocks exposed along the so-called Northern Paraguai Belt (location A in Fig.1). The newly acquired data are linked to the available regional geological information and the geological sequences are also compared with similar rock sequences preserved along strike in West Africa. The ultimate aim here is to better understand the Neoproterozoic to Cambrian evolution of this important part of the western Gondwana.

REGIONAL GEOLOGY

STRATIGRAPHY

The Northern Paraguai Belt is part of an important orogen related to the assembly of Gondwana that lies along the southern limit of the Amazonian Craton in central South America (Fig. 1). It is classically described as a fold and thrust belt with a supposedly adjacent foreland basin located immediately to the north and west (e.g. Almeida 1984; Alvarenga & Trompette 1993; Nogueira *et al*. 2007; McGee *et al*. 2014, 2015). The belt comprises older Tonian-Cryogenian metasedimentary rocks of the *Cuiabá Group* and younger Marinoan glacial deposits of the *Puga Formation*, Ediacaran limestones of the *Araras Group* and Cambrian-Ordovician siliciclastic rocks of the *Alto Paraguai Group* (Fig. 2; Fig. 3; Almeida 1964, 1984; Trompette 1994; Nogueira *et al*. 2003; Alvarenga *et al*. 2004, 2012; Nogueira & Riccomini 2006; Nogueira *et al*. 2007; Tohver *et al*. 2010, 2011; Bandeira *et al*. 2012; McGee *et al*. 2014, 2015; Santos *et al.* 2017; Nogueira *et al*. 2019).

The rocks of the Cuiabá Group (Almeida 1964, 1965) are turbiditic siliciclastic successions, deposited in a platformal setting, during early Neoproterozoic rifting of the Rodinia Supercontinent at about 1.2-0.8 Ga (Tokashiki & Saes 2008; Babinski et al. 2018). Sm/Nd whole-rock ages obtained in an attempt to elucidate the source-area for the Cuiabá Group rocks yield ages of 0.9-2.1 Ga (Babinski *et al*. 2018). According to these data, the rocks of the Amazonian Craton represent the main source area for the Cuiabá Group. These rocks underwent ductile deformation and greenschist facies metamorphism (Tokashiki & Saes 2008) and Ar/Ar cooling ages of 541±10 to 484±12 Ma have been obtained in these sequences (Geraldes *et al*. 2008; Tohver *et al*. 2010). Dating of ultramafic bodies intruded into the Cuiabá Group rocks, exposed in the Planalto da Serra region, have yielded an intrusion age of about 600 Ma (Rb/Sr and K-Ar; De Min *et al*. 2013).

Records of marine transgressions along the glacial platform during the Cryogenian/Ediacaran are thought to be related to the end of the Marinoan Glaciation, around 635 Ma ago (Kirschvink *et al*. 1997; Hoffman & Schrag 2002; Nogueira *et al*. 2003). The rocks of the Puga Formation are tillites with striated pebbles of sandstone, gneiss and granitic rocks, interpreted as Marinoan deposits (706±9 Ma U/Pb detrital zircon; Babinski *et al*. 2013) related to a glacially influenced platformal environment (Maciel 1959; Almeida 1964a, b; Alvarenga & Trompette 1992; Nogueira *et al*. 2003).

The Ediacaran Araras Group comprises four units: the Cap Dolostones of the *Mirassol d'Oeste Formation*, interpreted as part of a shallow marine platform; the *Guia Formation* representing limestones and bituminous shales interpreted as deep platformal deposits; the *Serra do Quilombo Formation*, which includes dolostones and dolomitic breccias associated with moderately deep to shallow platformal conditions and the *Nobres Formation* comprising dolomites, cherts, sandstones, carbonatic shales formed in a peri-tidal environment (Nogueira & Riccomini 2006; Brelaz 2012; Milhomem Neto *et al*. 2013). The maximum depositional ages of the rocks of the Mirassol d'Oeste and Guia formations are respectively provided by U/Pb detrital zircon ages and Pb/Pb whole rock ages in the range 627±32 to 622±33 (Babinski *et al*. 2006; Romero *et al*. 2013) and a U/Pb detrital zircon of 652±5 (Babinski *et al*. 2018). None of these rocks show any clear evidence of regional metamorphism, with organic matter widely preserved in the rocks of the Guia and Serra do Quilombo formations (Nogueira & Riccomini 2006; Brelaz 2012; Milhomem *et al*. 2013).

The western and northern segments of the Northern Paraguai Belt (Figs. 2 and 3) are also associated with siliciclastic rocks of the Alto Paraguai Group, which comprise Cambrian to Ordovician siliciclastic deposits including conglomerates, sandstones and shales interpreted as platformal sediments influenced by storms, waves and tides, grading up into the fluvial-lacustrine systems (Almeida 1964; Alvarenga & Saes 1992; Bandeira *et al*. 2007, 2012; Santos *et al*. 2017). The maximum depositional ages of the upper succession of the Alto Paraguai Group obtained by Ar/Ar (detrital muscovite) and U/Pb (detrital zircon) are 622 Ma and 544 Ma - 541 Ma, respectively (Bandeira *et al*. 2012; McGee *et al*. 2014, 2015). Records of *Skolithos* ichnofacies burrows in the rocks of the lowermost Alto Paraguai Group suggest a Lowermost Cambrian age or younger for these rocks (Santos et al. 2017).

All of the post-Cryogenian deposits have been interpreted as foredeep sediments laid down in a major foreland basin related to the Northern Paraguai Belt (Alvarenga *et al*. 2004; Nogueira *et al*. 2007;

Tohver *et al*. 2010 and 2011; Bandeira *et al*. 2012; McGee *et al*. 2014, 2015). A recently proposed alternative interpretation suggest that they represent an intracratonic basin sequence formed in the southern portion of the Amazonian Craton and related to eustatic transgressions that occurred during the Ediacaran-Cambrian (Nogueira *et al*. 2019).

The São Vicente Granite, dated at 518±4 Ma (U/Pb zircon; McGee *et al*. 2012), and the Mesozoic basalts of the Tapirapuã Formation, locally cut and post-date the rocks of Paraguai Belt (Montes-Lauar *et al*. 1994). Most of the Neoproterozoic/Cambrian rocks of the Cuiabá Group, the Puga Formation, the Araras and Alto Paraguai groups are also unconformably overlain by post-Ordovician sedimentary rocks of the Paraná and Parecis basins (Figs. 2; Fig. 3).

REGIONAL TECTONIC CONTEXT

The deformation of the Northern Paraguai Belt is thought to be related to the Brasiliano/Pan-African Orogeny, and has been described as a polyphase event that decreases progressively in intensity and metamorphic grade from E to W, towards the Amazonian Craton (Fig 1; Almeida 1964, 1984; Almeida & Hasui 1984; Alvarenga & Trompette 1993). It has been classically subdivided into three major structural domains in order to explain its deformation patterns and tectonic evolution (Almeida 1964, 1984; Alvarenga & Trompette 1993): an *Internal Zone* comprising metasedimentary rocks of the Cuiabá Group, mainly deformed by folds, thrust-faults and associated cleavages; an

External Zone including little metamorphosed sedimentary rocks of the Puga Formation, Araras and Alto Paraguai groups, also deformed by folds, sub-vertical thrust-faults and cleavage; and a *Platform Sedimentary Cover* which represents the same sequence of sedimentary rocks that are only weakly deformed.

Four deformation phases have been proposed to affect the rocks of the Northern Paraguai Belt (Luz *et al*. 1980; Souza 1981; Pires *et al*. 1986; Alvarenga 1986, 1990; Del'Rey Silva 1990; Alvarenga & Trompette 1993; Silva 1999; Silva *et al*. 2002; Costa *et al*. 2015; Vasconcelos *et al*. 2015). The first phase (D1) is thought to be responsible for the main deformation of rocks of the Cuiabá Group, exposed in the Internal Zone as isoclinal to tight folding, with an associated NE-SW trending cleavage (S1) and NE-SW reverse faults. The second (D2) and third deformation phases (D3) are thought to affect rocks in both the Internal and External zones, and are marked by the development of crenulation cleavages, NE-SW and NW-SE fractures, as well as open folds. A fourth deformation phase (D4) is mainly represented by fractures oriented perpendicularly to the main foliation trend, found in the sedimentary rocks of the External Zone.

The tectonic vergence of the belt is thought by some authors to be towards the NW (Almeida 1964, 1984; Nogueira & Oliveira 1978; Corrêa *et al.* 1979; Alvarenga 1986, 1990; and McGee *et al*. 2014, 2015), although Luz *et al*. (1980), Alvarenga & Trompette (1993), Costa *et al*. (2015) and Vasconcelos *et al*. (2015) propose an opposite southeastward vergence. Silva (1999) has suggested a model involving the presence of back-thrusts in order to explain the possibility of two contemporaneous and opposed tectonic vergence directions.

FIELD DATA - STRUCTURAL ANALYSES

The tectonic structures and the rocks of the Northern Paraguai Belt and its adjacent sedimentary cover are well exposed in road cuts and natural outcrops between Cuiabá, Guia, Poconé, Planalto da Serra, Nobres, Diamantino, Cáceres and Mirassol d'Oeste (Mato Grosso State) (Fig. 3). The three-dimensional geometry, inter-relationships and kinematics of the structures preserved, are illustrated in supported by field observations and structural data.

Geometric and kinematic analyses show that the complex, seemingly polyphase structures of the Northern Paraguai Belt are more simply interpreted in terms of progressive deformation and partitioning during two successive transpressional-transtensional episodes (following the concepts and models of Fossen *et al*. 1994; Dewey *et al*. 1998; Tikoff & Fossen 1999; Holdsworth *et al*. 2002; Jones *et al*. 2004; Fossen *et al*. 2018 for example). As shown in the following sections, the metasedimentary rocks of the Cuiabá Group have been deformed during a single episode of ductile transpression forming the 'Transpressional Structural Domain' (TPSD), whilst the younger sedimentary rocks of the Puga Formation and Araras-Alto Paraguai groups are affected by brittle transtensional deformation (Fig. 3) forming a later 'Transtensional Structural Domain' (TTSD). The younger brittle transtensional structures are also widely recognized locally overprinting the ductile TPSD structures in the Cuiabá Group.

TRANSPRESSIONAL STRUCTURAL DOMAIN (TPSD)

The rocks deformed by transpression outcrop mainly in the southeastern part of the surveyed region (Fig 3). They correspond to phyllites, metapelites, metaconglomerates and metasandstones of the Cuiabá Group (Fig. 4). The ductile to brittle-ductile deformation of these metasedimentary rocks forms a series of NE-SW and E-W-trending foliated domains (Fig. 3; Fig. 4). Fine continuous foliations (in phyllites) and spaced foliations (in the metapelites, metasandstones and metaconglomerates) are developed everywhere, both of which carry stretching lineations (Fig. 4; Figs. 5B, 5C, 5E). Compositional layering thought to correspond to bedding is preserved in less deformed regions (e.g. Fig. 5A). Regional to mesoscopic folds are observed deforming both the bedding and, locally, the continuous foliations (Fig. 3; Figs. 5A, 5B).

A regional-scale anastomosing network of higher strain NE-SW sinistral transpressional shear zones is recognized associated with sinistrally verging asymmetric folds. Two structural sub-domains sharing the same regional foliation can be defined based on the angular relationships between foliations and lineations (rake) in the shear zones. These reveal two quite distinct kinematic domains: (1) those with moderate lineation rake angles (typically ca. 30° to 40°); and (2) those with low rake angles (<10º), referred to here as TPSD-A and TPSD-B, respectively. The mapped extent of these structural domains is shown in Figure 3. Given the common regional foliation and ubiquitous sinistral vergence of associated minor structures, these are interpreted in terms of a partitioned transpressional deformation in the rocks of the Cuiabá Group with a regional vergence direction towards the SE.

The rocks of the TPSD-A sub-domain are mostly low-grade metasedimentary rocks that display bedding planes with NE-SW strikes and steep to gentle dips towards both the NW and SE (Figs. 5A, 5B). Recumbent to moderately reclined folds of bedding are common, with NE-SW axial planes and gentle plunging SW ß axis; vergence overall is to the SE (Fig. 5A). Sets of tens-to-hundred-meter wide NE-SW shear zones cut across these rocks, developing a fine continuous foliation in metapelites, with gentle to moderate dips towards NW and SE (Fig. 5B; Fig. 6). Stretching lineations associated with this continuous foliation are shallowly plunging towards the N, NW and NE, with typical rake angles of 30-40º (Fig. 5C; Fig. 6A). The fine continuous foliation is itself deformed by asymmetric moderately reclined folds indicating sinistral kinematics, with axial planes striking NE-SW, and a regional ß axis plunging gently NE, with a southeastward vergence direction (Fig.3; Fig. 5A). Oblique thrust-faults are observed both in regional and outcrop scales, with NE-SW strike and low angle dips towards the NW approaching sub-horizontal (Fig. 3; Fig. 5C; Fig. 6A). The inclined regional foliation, moderately plunging mineral lineations and associated sinistral shear criteria are consistent with an inclined transpressional deformation, possibly contraction-dominated (see for example Holdsworth *et al*. 2002; Jones *et al*. 2004)

The TPSD-B sub-domain (Fig.3; Fig.5) is characterized by much more highly deformed metasedimentary rocks in shear zones and shear bands, with a NE-SW anastomosing mylonitic foliation showing steep to sub-vertical dips towards NW and SE (Fig. 5D; Fig. 6C). Stretching lineations plunge consistently gently to the NE and SW, with a 10º average rake angle (Fig. 5E). The fine continuous foliation may show local transposition along shear bands, and sinistral asymmetric drag folds (Fig. 6C). The steep dips of the foliation with shallowly plunging associated mineral lineations and sinistral shear criteria suggest a wrench-dominated transpressional strain pattern (see for example Holdsworth *et al*. 2002; Jones *et al*. 2004).

Under the microscope, the fine grained metapelites of the Cuiabá Group in both sub-domains show fine grained spaced foliation defined by the aligned arrangement of muscovite, ribbons and aggregates of quartz and feldspar grains (Fig. 7). Aggregates of quartz and K-feldspar locally display discrete sinistral asymmetry (Figs. 7A, 7B). A set of conjugate crenulation cleavages (Fig. 8) with centimeter-scale spacing, show NE-SW and NW-SE strikes with gentle dips towards NW and SE and steep dips towards NE; vergence senses associated with this cleavage show consistent dextral asymmetry (Fig. 8B; Fig. 9A).

The fine continuous fabrics that dominate in the rocks of the Cuiabá Group are everywhere cut by sets of NW-SE, N-S, ENE-WSW and NE-SW sets of normal-oblique faults and fractures (Fig. 9B). Tabular quartz veins are found in metasandstones, metaconglomerates and phyllites of the Cuiabá Group. They range from a few millimeters to a few meters thick and lie parallel, subparallel, or discordant to the foliation of the metasedimentary rocks in the TPSD (Fig. 4C). They are NE-SW, NW-SE, N-S and E-W striking, with moderate to sub-vertical dips towards the NW, SW, NE and S, respectively (Fig. 9C). They are thought to be associated with the late normal-oblique faults and fractures. Some of these veins host important gold deposits, and are locally mined (Tokashiki & Saes 2008; Vasconcelos *et al*. 2015).

TRANSTENSIONAL STRUCTURAL DOMAIN (TTSD)

The sedimentary rocks of the Puga Formation, Araras Group and Alto Paraguai Group include pelites, tillites, dolostones, calcitic shale, sandstones and shales (Fig. 2; Fig. 10), which are juxtaposed by normal faulting against the rocks of Cuiabá Group to the southeast (Fig. 3). Deformation here is characterized by normal-oblique faults, drag folds, fractures/joints, and locally developed cataclastic foliations (Figs. 11; Fig. 15).

The main sets of normal-oblique and strike-slip faults observed in the sedimentary rocks trend NE-SW, NW-SE, N-S and E-W (Fig. 11C, 11I, 11N). The NE-SW normal-oblique faults have steep to sub-vertical planes, dipping towards the NW and SE, with shallowly SW plunging oblique striations showing NW-side down, sinistral kinematics (Figs. 11D, 11F, 11I, 11J, 11N, 11O). The NW-SE normal-oblique faults also have steep to sub-vertical dips towards SW, and shallowly NW plunging striations showing SE-side down, dextral oblique kinematics (Figs. 11D, 11F, 11I, 11J, 11N, 11O). The N-S normal-oblique faults have steep to sub-vertical dips towards E and W, and show down-dip to oblique-dip striations with a shallow northward plunge (Figs. 11D, 11F, 11I, 11J, 11N, 11O). The E-W strike-slip faults show steep to sub-vertical dip angles towards the N and S and show shallowly E or W plunging striations (Figs. 11D, 11F, 11I, 11J, 11N, 11O). The asymmetry of the regional and mesoscopic drag folds located near to the NE-SW and NW-SE trending normal oblique faults indicates a mainly dextral sense of shear, suggesting a dextral transtension.

The NE-SW, NW-SE and E-W normal-oblique and strike-slip faults, described above, are responsible for local to regional drag folding in the sedimentary rocks (Figs. 11A, 11F, 11K; Fig. 12). Fold axis are moderately to shallowly plunging SE, SW and NE (Figs. 12B, 12C); associated axial planes strike NE-SW with steep dips towards NW, as well as NW-SE with moderate to steep dips towards the NE (Fig. 11B, 11G, 11L). These fault-related folds are moderately reclined to upright, open to tight, with variable vergence towards either the SW or SE; the overall asymmetries of the brittle mesoscopic drag folds are consistent with regional dextral kinematics (Figs. 11A, 11F, 11K; Fig. 12).

A cataclastic foliation cuts both metasedimentary rocks of the TPSD and the sedimentary rocks of the TTSD and is closely related to the presence of the normal-oblique and strike-slip faults and fractures and associated folds (Fig. 12). It shows mainly N-S to NNE-SSW strikes, with moderate to sub-vertical dips towards the SE (Fig. 11E). This non-penetrative foliation develops in tens to hundreds of meters wide corridors that are hundreds of meters to kilometers long in map view. It is found in all rocks of the Northern Paraguai Belt and is an anastomosing foliation that locally transposes all earlier structures (Fig. 6C; Fig. 12).

A notably large set of folds is observed near the Nossa Senhora da Guia city (Fig.3; Fig. 13), north of Cuiabá and corresponds to a ca. 20 km long and ca. 3 km wide synclinal structure deforming calcitic shales and limestones of the Guia Formation (Nogueira & Riccomini 2006; Brelaz 2012), and faulted against the Cuiabá Group metasedimentary rocks. This large fold has been attributed by Almeida (1964, 1984), Luz *et al*. (1980) and Alvarenga & Trompette (1993) to the effects of the Brasiliano/Pan-African Orogeny affecting the younger sedimentary rocks in the region.

Our field observations show that near the borders of the syncline, the metapelites of the Cuiabá Group have developed a pervasive NE-SW continuous foliation dipping 55º-60º towards the NW (Fig. 14). These rocks form part of the TPSD-A sub-domain (Fig. 3). The major syncline - defined by folded and faulted bedding is developed in limestones of the younger Guia Formation rocks that are inferred, based on their unmetamorphosed state, to have originally unconformably overlain the metasedimentary rocks of the Cuiabá Group. The bedding inside the syncline is mostly flat, and is only folded and rotated into steep 65º-85º NW dips adjacent to the bounding normal fault. Fold hinges are parallel to the NE-SW normal fault planes, plunging shallowly to sub-horizontally towards the NE and SW (Fig. 13; Fig. 14). The contacts between the sedimentary and metasedimentary rocks are NE-SW normal-oblique fault zones with steep dips (75º-85º) towards NW and SE (Fig. 13; Fig. 14).

SUMMARY

The exposed metasedimentary rocks of the Cuiabá Group show pervasive effects of ductile deformation in which two structural sub-domains of partitioned transpressional deformation are recognized (Fig. 3). The TPSD-A domain is characterized by shallow to moderately-dipping NE-SW shear zones, fine continuous foliation and stretching lineations with rakes of about 40º, consistent with a sinistral contraction-dominated transpression. The TPSD-B domain has high strain sinistral shear zones with moderately to subvertically dipping mylonitic foliations and shallowly plunging stretching lineations (rakes around 10º), suggesting a wrench-dominated transpression. The rocks related to both structural sub-domains share the same regional foliation and show a consistent tectonic vergence towards the SE. Metamorphism is low to medium greenschist facies (Tokashiki & Saes 2008).

The late-Cryogenian to Cambrian rocks of the Puga Formation, Araras and Alto Paraguai groups, exposed in the northern and western region of the Northern Paraguai Belt, have not experienced regional metamorphism (Nogueira & Riccomini 2006; Brelaz 2012; Milhomem Neto *et al*. 2013) and show no ductile transpressional deformation. Deformation in these younger sedimentary sequences is marked by brittle oblique-slip faults and shear zones in a range of orientations with cataclastic foliations locally developed. Folds are present here, but are interpreted to be normal oblique faults-related drag structures. The folds are drag or strike-slip-related features as are found in other transtensional settings (e.g. De Paola *et al*. 2005). These are asymmetric, moderately inclined to upright and show no consistent vergence pattern. These structures are consistently found adjacent to NE-SW normal oblique faults suggesting that they were formed during transtensional regional deformation in the TTSD.

The rocks of Cuiabá Group locally display NE-SW, NW-SE, N-S and E-W-trending zones of late dextral crenulation cleavage, which transects the older fine continuous foliations. This cleavage is developed sub-parallel to the TTSD brittle features and is interpreted to represent zones of overprinting grain-scale brittle deformation developed preferentially in mica-rich metasedimentary rocks.

DISCUSSION

THE AGES OF BASEMENT AND COVER

The Brasiliano/Pan-African Orogeny is generally related to the tectonic assembly of the western Gondwana. This event is thought to be responsible for the deformation and metamorphism of the Cuiabá Group rocks in the Northern Paraguai Belt (Fig.3).

De Min *et al*. (2013) used K/Ar, Ar/Ar and Rb/Sr geochronology to suggest an age of 600 Ma for the intrusion of ultramafic bodies into the Cuiabá Group, and Babinski *et al*. (2018) have obtained a U-Pb detrital zircon age of 652±5 Ma for the calcitic limestones of the Guia Formation. Importantly, our findings suggest that the Guia Formation should be included in the Araras Group, and that it is *not* part of the Northern Paraguai Belt basement. These rocks show neither metamorphism or transpressional ductile deformation, contrary to previously suggestions made by Luz *et al.* (1980), Tokashiki & Saes (2008) and McGee *et al*. (2015). This implies that both the Cuiabá Group and its associated transpressional ductile deformation and metamorphism are *older* than 652-600 Ma. Thus, there is no field or other evidence to support the idea that Brasiliano/Pan-African metamorphism and ductile deformation continued into the Cambrian-Ordovician.

Based on our structural observations in the field and thin section, we suggest that the Cambrian-Ordovician Ar/Ar cooling ages recorded by the Cuiabá Group (Geraldes *et al.* 2008; Tohver *et al.* 2010) are most likely related to post-collisional overprinting. This could very well be related to the development of the transtensional faults and associated drag folds which are found both in the Neoproterozoic metasedimentary rocks and in the Ediacaran to early Cambrian sedimentary cover sequences.

IS A FORELAND BASIN PRESENT?

Luz *et al.* (1980), Almeida *et al*. (1984), Alvarenga & Trompette (1993), Nogueira *et al*. (2007) Alvarenga *et al*. (2012), Bandeira *et al*. 2012 and McGee *et al*. (2014, 2015) have argued that the rocks of the Cuiabá Group, Puga Formation, Araras and Alto Paraguai groups represent a fold and thrust and foreland-foredeep system in which the tectonic deformation was driven by the continuous shortening of the adjacent orogen.

A foreland basin typically is related to down-flexure of the lithosphere in response to an orogenic load advancing towards the foreland in the direction of tectonic vergence (DeCelles *et al*. 2002). According to Almeida (1964, 1984), Nogueira & Oliveira (1978), and Corrêa *et al*. (1979), Alvarenga (1986, 1990) and McGee *et al*. (2014, 2015). This would require the orogenic vergence to be from the SE towards the NW. Conversely, Luz *et al.* (1980), Alvarenga & Trompette (1993), Costa *et al.* (2015) and Vasconcelos *et al*. (2015) suggest that the vergence was from NW towards the SE. Our structural mapping confirms that the sinistral partitioned transpressional deformation (i.e. the

TPSD), developed in the metamorphic rocks of the Cuiabá Group, has a consistent SE vergence (e.g. Fig. 3; Fig. 5; Fig. 6). This would require that any foreland sedimentary succession should lie to the southeast of the collisional belt, not to the northwest, i.e. if present, it would lie below the rocks of the younger Paraná Basin.

Previous stratigraphic investigations (Alvarenga & Saes 1992; Nogueira *et al*. 2003; Alvarenga *et al*. 2012; Nogueira & Riccomini 2006; Bandeira *et al.* 2012; Santos *et al*. 2017; Nogueira *et al*. 2019) show that the thick sedimentary cover of the Puga Formation and Araras and Alto Paraguai groups are a succession of glacially influenced deep to shallow marine platform influenced by storms, tides and waves grading up to lacustrine-fluvial system. Well preserved Silurian to Neogene foreland basins (like those found adjacent to the Pyrenees, Alpine-Himalayan system, the Zagros, North Caucasus, South Urals, Appalachian and Andes thrust belts) typically comprise immature sedimentary rocks normally from fluvial/alluvial-fan to a shallow marine platformal paleoenvironments, showing wedge-shaped stratigraphic sequences and a variety of unconformities due the tectonic instability and rapid subsidence rates (Allen & Allen 1990; DeCelles & Giles 1996; DeCelles *et al*. 2002; Chapman & DeCelles 2015). These rocks generally also show progressive metamorphism and zonation of folds and thrust faults, consistent with the progressive foreland-directed advance of the orogenic wedge (Allen *et al*. 1991; Saura *et al.* 2011; Zhang *et al.* 2011; Delgado *et al.* 2012; Mouthereau *et al*. 2014; Roigé *et al.* 2017). None of these characteristics are seen in the Ediacaran-Cambrian sedimentary rocks of the Northern Paraguai Belt.

The present structural analyses and previous stratigraphic models (Nogueira *et al*. 2003; Nogueira & Riccomini 2006; Bandeira *et al.* 2012; Santos *et al*. 2017; Nogueira *et al*. 2019) suggest that an unconformity exists between the metasedimentary basement rocks of the Northern Paraguai Belt and the younger unmetamorphosed sedimentary cover sequences. Stratigraphic and sedimentological analyses and the general regional tectonic setting seem more consistent with the cover sequences being part of an intracratonic basin, as suggested by Nogueira *et al*. (2019).

COMPARISONS WITH SIMILAR SEQUENCES IN AFRICA

The Brasiliano/Pan-African Orogeny is also recognized in the western part of the West African Craton (Dalziel 1992; Trompette 1994; Tokashiki & Saes 2008; Deynoux *et al*. 2006; Villeneuve 2008). The Rockelides-Bassarides belts have been correlated with the Araguaia and the Northern Paraguai belts based on similarities in general tectonic setting, lithostratigraphy and geochronology (Fig. 15; Trompette 1994, 1997; Villeneuve & Cornée 1994; Shields *et al*. 2007; Deynoux *et al*. 2006; Villeneuve 2008; Paixão *et al*. 2008).

Regionally in the Northern Paraguai Belt, siliciclastic successions, deposited ca. 1.2-0.8 Ga during rifting of Rodinia forming a deep to shallow marine platform, are thought to correspond to the protolith of the

Cuiabá Group metasedimentary rocks (Dalziel 1992; Tokashiki & Saes 2008; Babinski *et al*. 2018). The metamorphic rocks of the Termesse and Guinguan groups, exposed in the Bassarides Belt in southwestern West African Craton (Fig. 15), are similarly related to platformal basins, and are further constrained by Rb/Sr ages obtained from rhyolites thought to date their emplacement between 1.0-1.05 Ga (Villeneuve 2008). The Termesse and Guinguan groups (Fig. 15B) are metavolcanosedimentary and ultramafic rocks whose metamorphic grade ranges from greenschist to amphibolite, that are locally intruded by granitoids, rhyolite, dacite and basalts. They are widely deformed by recumbent to open folds, schistosity and brittle cleavages (Bassot 1966; Villeneuve 1982, 1984).

The Bassarides Belt (Fig. 1) is overlain by a flat-lying Paleozoic sedimentary cover, which is correlated with the cratonic sedimentary rocks of Taoudéni Basin in the central portion of the West African Craton (Fig. 1; Fig. 15). In its lower parts, a sequence of Ediacaran to Cambrian sedimentary rocks (Fig. 15) forms the Mali and Batapa groups which unconformably overlie the Bassarides Belt (Villeneuve 2008). These sedimentary rocks include Marinoan tillites of the Walidiala Formation capped by 1000m of cap dolostones, shales, pelites and sandstones interpreted as having been deposited in a new phase of rifting between 610-550 Ma (Deynoux *et al*. 2006).

There are obvious similarities between the geological relationships shown by the ductile deformed parts of the Northern Paraguai and

Bassarides belts, and their geological relationships to overlying and adjacent Late Cryogenian to Early Cambrian Marinoan tillites, cap dolostones and siliciclastic sedimentary rocks (Fig. 15). This agrees with the suggestions of Shields *et al*. (2007) and Villeneuve (2005, 2008) who pointed out that both the rocks of Bassarides Belt and western Taoudéni Basin show stratigraphic and geochronological similarities to those outcropping in the northern areas of the Araguaia and Northern Paraguai belts, in South America (Fig. 16).

SYNTHESIS & CONCLUSIONS

Regionally in the Northern Paraguai Belt, siliciclastic successions forming the protoliths of the Cuiabá Group basement are thought to have been deposited ca. 1.2-0.8 Ga during rifting of Rodinia forming a deep to shallow marine platform (Fig 16A; Tokashiki & Saes 2008; Babinski *et al*. 2018). The structural analyses presented here show that the metasedimentary rocks of the Cuiabá Group were then deformed during Brasiliano/Pan African ductile sinistral partitioned transpression at about 652-600 Ma (Fig 16B; De Min *et al*. 2013; Babinski *et al*. 2018). The rocks forming this orogen were then unconformably overlain by late-Cryogenian to Cambrian sedimentary rocks (Puga Formation, Araras and Alto Paraguai groups), possibly during a Marinoan eustatic transgression (Fig 16C) as suggested by Nogueira *et al.* (2019).

Both the rocks of the Cuiabá Group and the late-Cryogenian/Cambrian sedimentary cover were later deformed by possibly post-Ordovician brittle transtensional structures. This formed both the dextrally verging crenulation fabric developed in the Cuiabá Group basement rocks and the transtensional deformation seen in the late-Cryogenian/early-Cambrian sedimentary sequences (Fig. 16D). In our view, there is no evidence for the existence of a foreland basin at this time and there is therefore no need to extent the effects of orogenesis into the Cambrian.

The model proposed requires the development of a large extensional-transtensional regional basin under the influence of the post-glacial eustatic transgression that took place after the Brasiliano/Pan-African Orogeny and Marinoan Glaciation (e.g. Fig. 16C). The presence of very similar successions in Western Africa may indicate that this formed part of an important regional intracontinental episode of basin formation that took place after the Early Cambrian along large parts of the eastern border of the West African/Amazonian cratons in western Gondwana.

Finally, sets of very late ENE-WSW normal faults, found in the rocks of the Northern Paraguai Belt (Fig. 16E), are known to be related to Mesozoic rifting during opening of the Atlantic Ocean (Martinelli 1998). The basalts of the Tapirapuã Formation (Montes-Lauar 1994), exposed in the northwestern region of the Northern Paraguai Belt (Fig. 3), are geochemically analogous to the Jurassic basalts of the Serra Geral Formation, overlying the Paleozoic rocks of the Paraná Basin (Barros *et al.* 2007).

Overall, this study highlights that events related to the assembly of the Western Gondwana during the Brasiliano/Pan-African Orogeny (ca. 650-600 Ma) and later intracontinental thermal subsidence or rifting episodes are well preserved in the Northern Paraguai Belt and can be broadly related to very similar sequences in Africa.

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Figure Captions

Fig. 1. Palaeogeographic reconstruction of West Gondwana showing the central and northeastern parts of the South American platform and northwestern Africa which assembled during the Brasiliano/Pan-African Orogeny (adapted from Villeneuve 2008 and Cordani *et al*. 2013).

Fig. 2. Tectono-stratigraphic framework of the Northern Paraguai Belt rocks, according to previous authors (Nogueira *et al*. 2003; Tokashiki & Saes 2008; Bandeira *et al*. 2012; McGee *et al*. 2012, 2015; Babinski *et al*. 2013, 2018; Santos *et al*. 2017; Nogueira *et al*. 2019).

Fig. 3. (A) Structural-geological map of the Northern Paraguai Belt and its Ediacaran to Early Cambrian cover, and; (B) NW-SE (X-X') cross-section showing the tectonic arrangement of the rocks and their structural domains. The locations of Figs 6, 12 and 13 are also shown, as are the locations of the contraction- and wrench-dominated transpression sub-domains in the TPSD.

Fig. 4. Cuiabá Group lithologies in the field (A) bedded metapelite, (B) phyllite, (C) conglomeratic metasandstone, (D) metasandstones and metapelites with bedding and cleavage, (E) sinistral shear bands and drag folds in metasandstone and (F) stretching lineation in fine continuous foliation in metapelites.

Fig. 5. Stereonets of structural data from the metasedimentary rocks of Cuiabá Group. (A) Poles to bedding showing partial girdle related to the development of moderately reclined folds, with NE-SW axial planes and a regional beta axis plunging shallowly SW. (B) Generally NE-SW trending fine continuous foliation showing girdle pattern with beta axis plunging gently NE. (C) NE-SW oblique-thrust faults with stretching lineations plunging gently N, NE and NW. (D) Generally NE-SW trending mylonitic foliation with moderate to high dip angles mainly towards the NW. (E) Gently NE or SW plunging stretching lineations associated with mylonitic foliation. The subdivision into the two domains A and B is based on the difference in stain intensity and lineation rakes. It is suggested that domain B is the product of a wrench dominated transpressional deformation.

Fig. 6. Structural cross-sections of structures in key outcrops in the Cuiabá Group. (A) Metasandstone in the TPSD-A domain showing reclined to recumbent folds, associated with a NE-SW sub-horizontal oblique thrust-fault pervasively cut by later NNE-SSW normal fault sets. (B) metapelites in the TPSD-A showing NE-SW foliation cross-cut by NE-SW and NW-SE normal faults. (C) mylonitic phyllonites in the TPSD-B domain

with an ENE-WSW fine continuous foliation and sinistral NE-SW sub-vertical shear bands, cut by NW-SE and NE-SW sub-vertical sets of normal faults. For locations of outcrops see Fig. 3. Both the rocks of sections (B) and (C) also preserve syn- to late-kinematic quartz veins.

Fig. 7. Photomicrographs of rocks of the Cuiabá Group. (A) and (B) show fine grained metapelites with a spaced foliation defined by the alignment of micas and lenticular polycrystalline quartz grain aggregates with slight sinistral asymmetry.

Fig. 8. (A) Metapelites of the Cuiabá Group showing NE-SW zonal crenulation cleavage affecting the older fine continuous fabric with dextral kinematic. (B) photomicrography of fine grained phyllite exhibiting fine continuous fabric deformed by dextrally verging crenulation cleavage.

Fig. 9. (A) Pole to planes of NE-SW, NW-SE, N-S and E-W crenulation cleavage with steep to sub-vertical dips towards the SE, NW, SW and N; note that generally NE-SW strikes are dominant. (B) ENE-WSW, NE-SW and NE-SW normal oblique faults with steep to moderate dips towards the N, S, SW and NE to sub-vertical. (C) sub-vertical NW-SE, NE-SW and E-W trending quartz veins in the Cuiabá Group rocks.

Fig. 10. Sedimentary rocks exposed in the northern and western portion of the Northern Paraguai Belt: (A) diamictite of the Puga Formation. (B) Cap dolostones of the Mirassol d’Oeste Formation. (C) Calcitic limestones of the Guia Formation. (D) Dolostones of the Nobres Formation. (E) sandstones of the Raizama Formation. (F) Shales of the Diamantino

Formation. In all cases note the dominance of bedding and lack of pervasive ductile deformation fabrics.

Fig. 11. (A), (F) and (K) Stereonets of poles to bedding in the sedimentary rocks of the Transtensional Structural Domain (TTSD) with general NE-SW strike and gentle to steep or sub-vertical dips towards the NW and SE, for the Cáceres, Nobres and Planalto da Serra areas, respectively (for location, see Fig 3). The observed girdles are related to upright to moderately inclined brittle drag folds, with NE-SW and NW-SE striking axial planes (B, G and L) and (H and M) hinges with moderate to gentle plunges towards the ENE, SE and SW. (C, I and N) NE-SW, NW-SE and N-S normal oblique faults and E-W sub-vertical faults, (D, J and O) with gentle to moderately plunging slickensides towards NW, N, NE, SW and SW. (E) Cataclastic foliations that cross-cut older ductile structures in the Northern Paraguai Belt rocks, with sub-vertical NE-SW and NW-SE strikes.

Fig. 12. (A), (B) and (C) Cross-sections in dolomites of the Serra do Quilombo Formation and sandstones of the Raizama Formation (for locations see Fig. 3) showing NE-SW and ENE-WSW striking bedding, locally cut by N-S, NNW-SSE, NE-SW and ENE-WSW sub-vertical normal oblique fault zones, rotating the bedding plane and forming forced drag folds.

Fig. 13. (A) Geological map and (B) cross-section of the contact region between de metasedimentary rocks of the Cuiabá Group with calcitic limestones of the Guia Formation, Mina da Brita, NW of N. S. da Guia city

(see Fig. 3 for location). The contact is defined by a NE-SW normal oblique fault. The Cuiabá Group rocks are steeply dipping and the limestones are deformed by drag folds related to dextral oblique normal faulting.

Fig. 14. Tectonic contact between metapelites of the Cuiabá Group with NE-SW trending fine continuous foliation (to the right) and NE-SW trending beds of the calcitic limestones of the Guia Formation (to the left), observed in the Mina da Brita (see Fig. 13). A regional NE-SW normal oblique fault cuts both the foliation of the metasedimentary rocks and the beds of the sedimentary sequence, forming an asymmetrical drag or forced synformal fold.

Fig. 15. (A) Stratigraphic summary of the Northern Paraguai fold and thrust Belt and Late Cryogenian to Cambrian sedimentary cover (adapted from Nogueira & Riccomini 2006; Bandeira *et al*. 2012; Alvarenga *et al*. 2012; Santos *et al*. 2017; Nogueira *et al*. 2019). (B) Stratigraphic sequence summary for the Bassarides Belt and Taoudéni Basin in Africa (adapted from Trompette 1973; Villeneuve 2005, 2008; Deynoux *et al*. 2006).

Fig. 16. Summary sequence showing the main tectonic episodes proposed for the regional development for the Northern Paraguai fold and thrust Belt and subsequent Ediacaran-Early intracratonic basin. (A) Rifting of Rodinia Supercontinent and establishment of oceanic basin in which the protoliths of the Cuiabá Group were deposited. (B) Brasiliano/Pan-African Orogeny including greenschist metamorphism and ductile sinistral

partitioned transpressional deformation verging towards the SE. (C) Uplift and erosion of the orogen and post-glacial transgression succeeded by the development of an intracratonic basin, thermal subsidence and late intrusion of the São Vicente Granite (ca. 518 Ma). (D) Brittle deformation, dextral oblique normal faulting and forced drag folding in the sedimentary rocks and brittle overprinting in the underlying basement of the Cuiabá Group and (E) Younger rift basin development including Mesozoic opening of the S Atlantic.

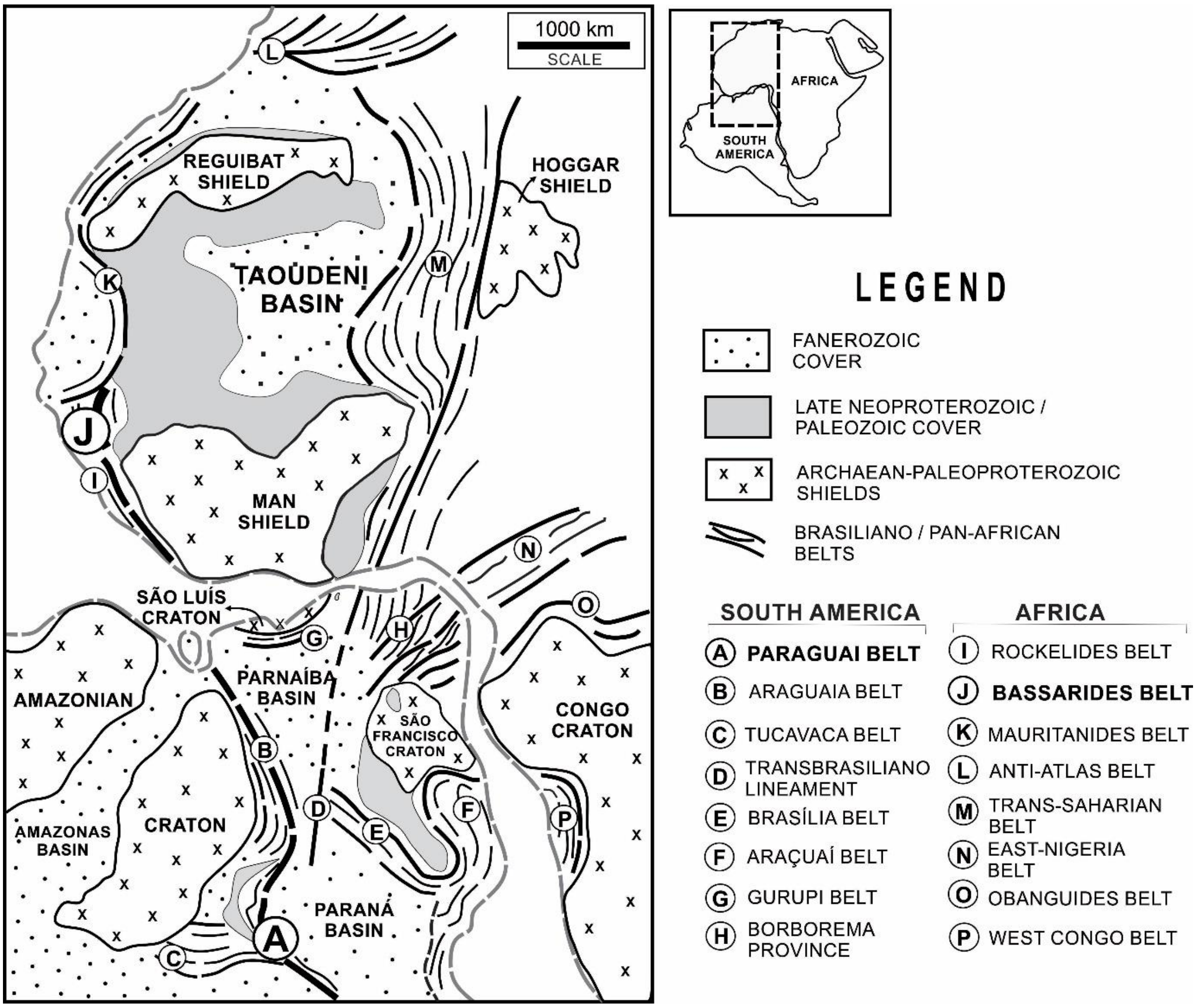

1000 km
SCALE
REGUIBAT SHIELD
TAOUDENI BASIN
HOGGAR SHIELD
MAN SHIELD
SÃO LUÍS CRATON
AMAZONIAN CRATON
AMAZONAS BASIN
PARNAÍBA BASIN
SÃO FRANCISCO CRATON
CONGO CRATON
PARANÁ BASIN
AFRICA
SOUTH AMERICA
LEGEND
FANEROZOIC COVER
LATE NEOPROTEROZOIC / PALEOZOIC COVER
ARCHAEAN-PALEOPROTEROZOIC SHIELDS
BRASILIANO / PAN-AFRICAN BELTS
SOUTH AMERICA
A PARAGUAI BELT
B ARAGUAIA BELT
C TUCAVACA BELT
D TRANSBRASILIANO LINEAMENT
E BRASÍLIA BELT
F ARAÇUAÍ BELT
G GURUPI BELT
H BORBOREMA PROVINCE
AFRICA
I ROCKELIDES BELT
J BASSARIDES BELT
K MAURITANIDES BELT
L ANTI-ATLAS BELT
M TRANS-SAHARIAN BELT
N EAST-NIGERIA BELT
O OBANGUIDES BELT
P WEST CONGO BELT

Fig. 1.

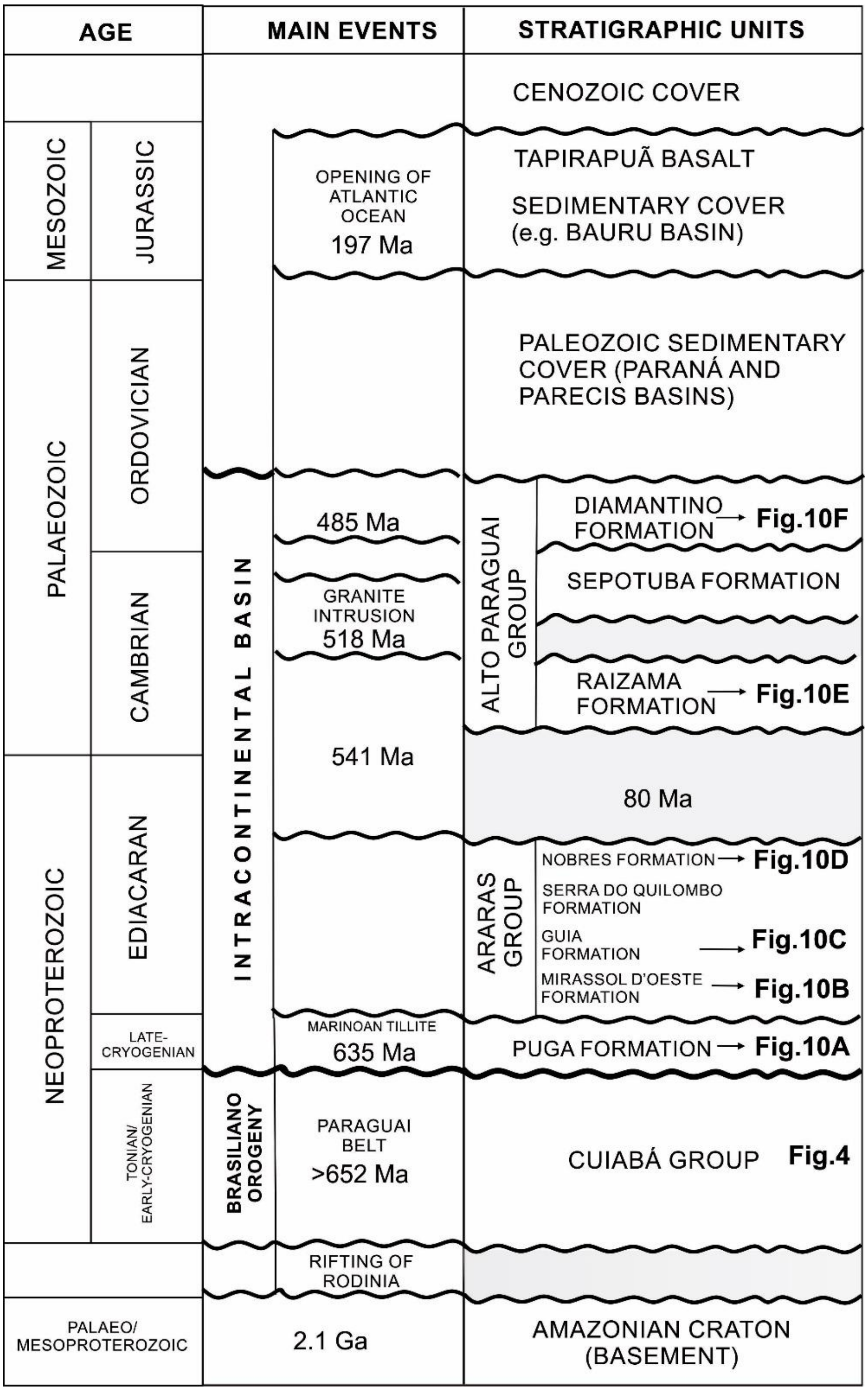

AGE
MAIN EVENTS
STRATIGRAPHIC UNITS
CENOZOIC COVER
MESOZOIC
JURASSIC
OPENING OF ATLANTIC OCEAN
197 Ma
TAPIRAPUÃ BASALT
SEDIMENTARY COVER (e.g. BAURU BASIN)
PALAEOZOIC
ORDOVICIAN
PALEOZOIC SEDIMENTARY COVER (PARANÁ AND PARECIS BASINS)
485 Ma
DIAMANTINO FORMATION → Fig.10F
ALTO PARAGUAI GROUP
SEPOTUBA FORMATION
CAMBRIAN
GRANITE INTRUSION
518 Ma
RAIZAMA FORMATION → Fig.10E
INTRACONTINENTAL BASIN
541 Ma
80 Ma
NEOPROTEROZOIC
EDIACARAN
ARARAS GROUP
NOBRES FORMATION → Fig.10D
SERRA DO QUILOMBO FORMATION
GUIA FORMATION → Fig.10C
MIRASSOL D'OESTE FORMATION → Fig.10B
LATE-CRYOGENIAN
MARINOAN TILLITE
635 Ma
PUGA FORMATION → Fig.10A
TONIAN/ EARLY-CRYOGENIAN
BRASILIANO OROGENY
PARAGUAI BELT
>652 Ma
CUIABÁ GROUP
Fig.4
RIFTING OF RODINIA
PALAEO/ MESOPROTEROZOIC
2.1 Ga
AMAZONIAN CRATON (BASEMENT)

Fig. 2.

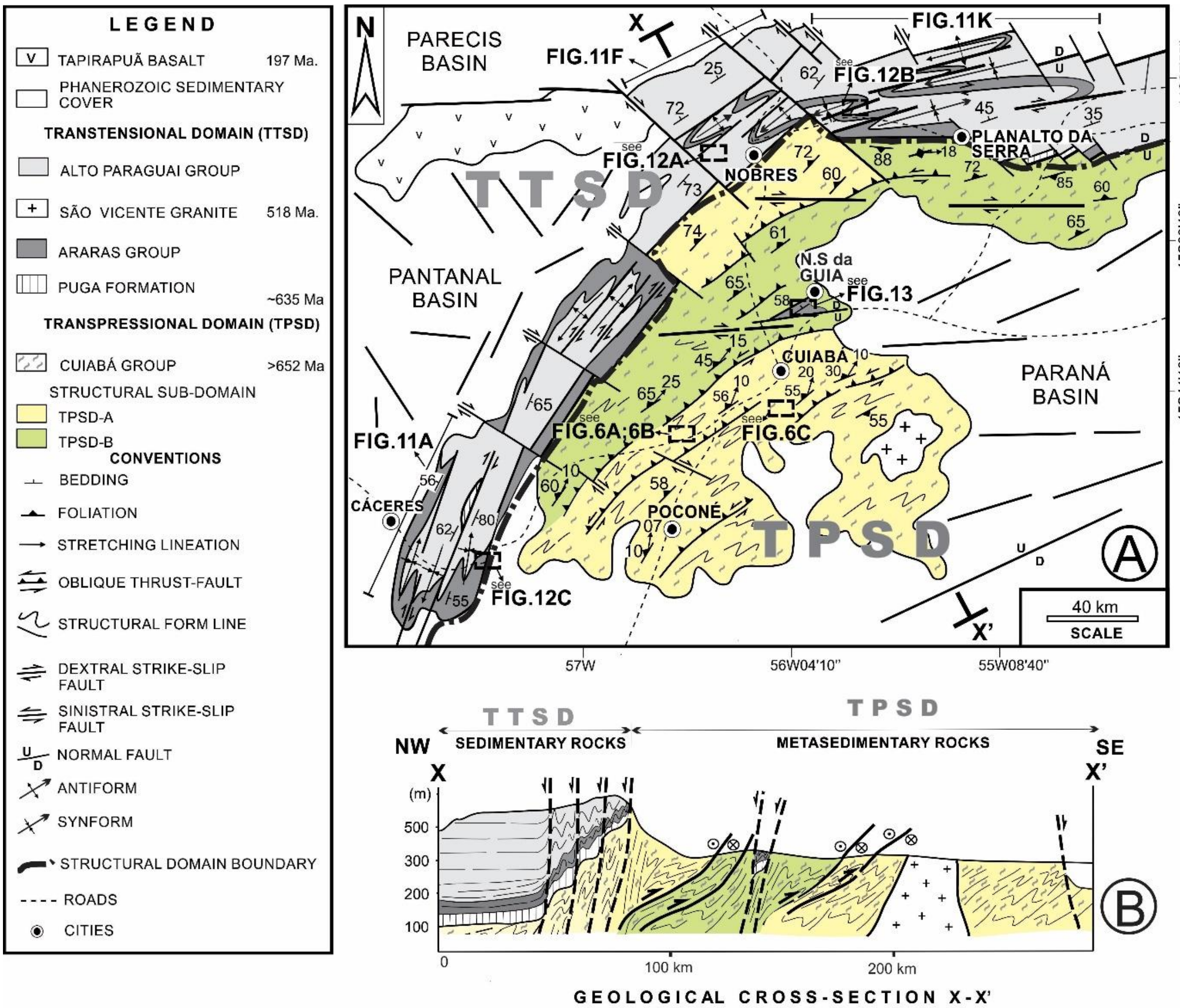

LEGEND
TAPIRAPUÃ BASALT 197 Ma.
PHANEROZOIC SEDIMENTARY COVER
TRANSTENSIONAL DOMAIN (TTSD)
ALTO PARAGUAI GROUP
SÃO VICENTE GRANITE 518 Ma.
ARARAS GROUP
PUGA FORMATION ~635 Ma
TRANSPRESSIONAL DOMAIN (TPSD)
CUIABÁ GROUP >652 Ma
STRUCTURAL SUB-DOMAIN
TPSD-A
TPSD-B
CONVENTIONS
BEDDING
FOLIATION
STRETCHING LINEATION
OBLIQUE THRUST-FAULT
STRUCTURAL FORM LINE
DEXTRAL STRIKE-SLIP FAULT
SINISTRAL STRIKE-SLIP FAULT
NORMAL FAULT
ANTIFORM
SYNFORM
STRUCTURAL DOMAIN BOUNDARY
ROADS
CITIES
PARECIS BASIN
PANTANAL BASIN
PARANÁ BASIN
TTSD
TPSD
FIG.11F
FIG.11K
FIG.12A
FIG.12B
FIG.12C
FIG.13
FIG.11A
FIG.6A;6B
FIG.6C
NOBRES
PLANALTO DA SERRA
N.S da GUIA
CUIABÁ
POCONÉ
CÁCERES
X
X'
40 km
SCALE
A
14S27'55"
15S03'13"
15S44'18"
57W
56W04'10"
55W08'40"
TTSD
SEDIMENTARY ROCKS
TPSD
METASEDIMENTARY ROCKS
NW
SE
(m)
500
300
200
100
0
100 km
200 km
B
GEOLOGICAL CROSS-SECTION X-X'

Fig. 3.

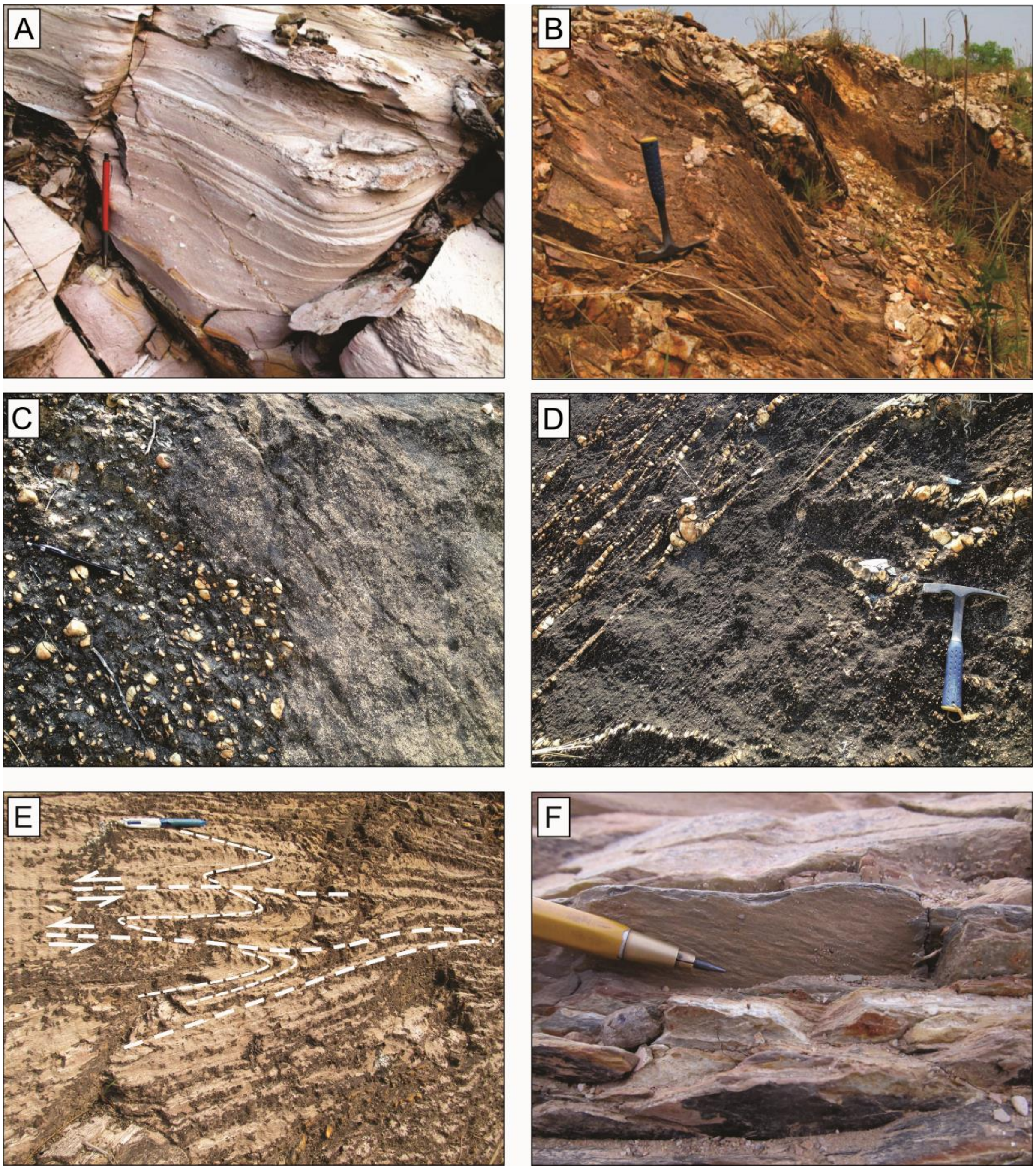


Fig. 4.

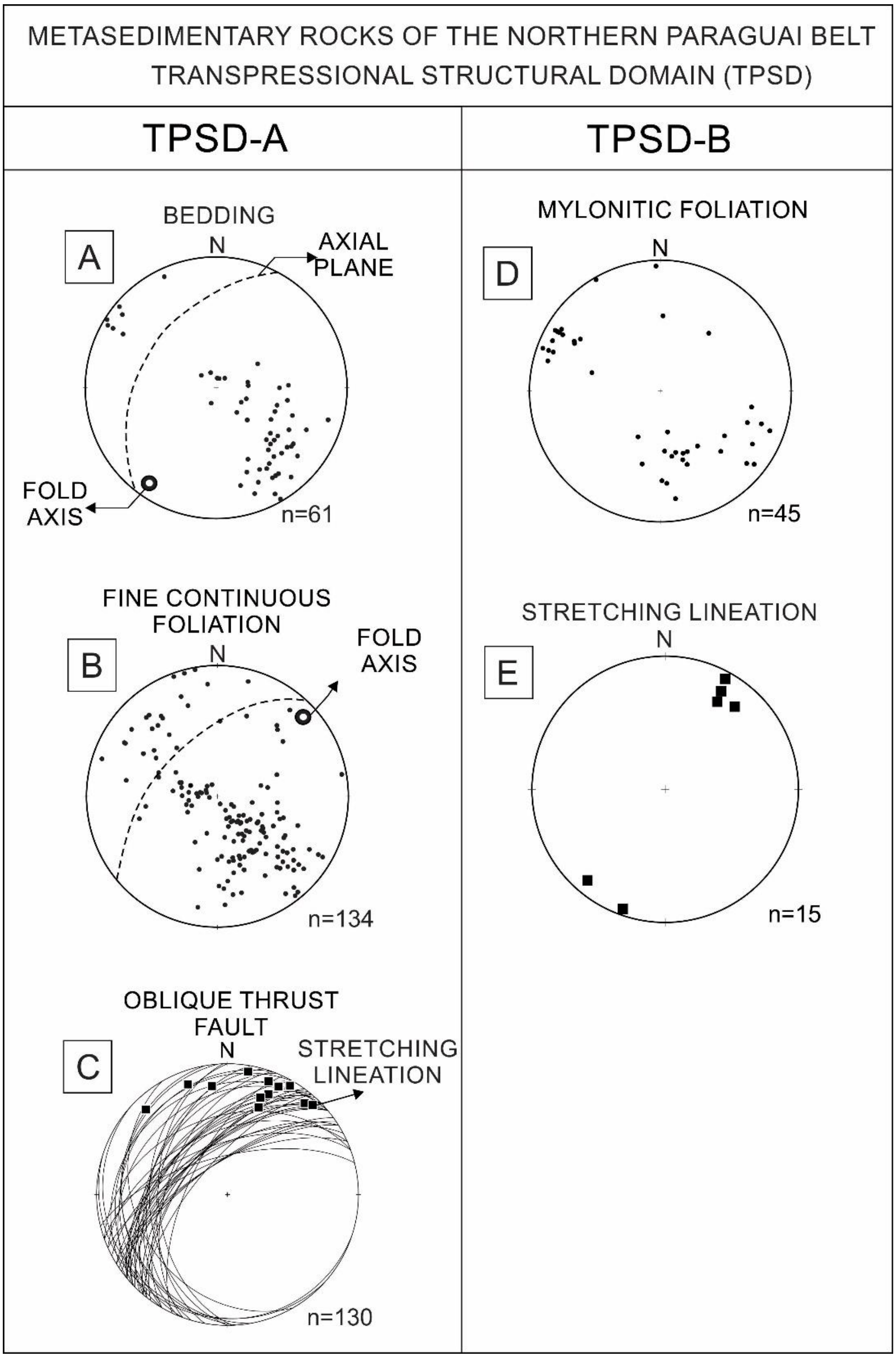

METASEDIMENTARY ROCKS OF THE NORTHERN PARAGUAI BELT
TRANSPRESSIONAL STRUCTURAL DOMAIN (TPSD)
TPSD-A
TPSD-B
BEDDING
A
N
AXIAL
PLANE
FOLD
AXIS
n=61
MYLONITIC FOLIATION
D
N
n=45
FINE CONTINUOUS
FOLIATION
B
N
FOLD
AXIS
n=134
STRETCHING LINEATION
E
N
n=15
OBLIQUE THRUST
FAULT
C
N
STRETCHING
LINEATION
n=130

Fig. 5.

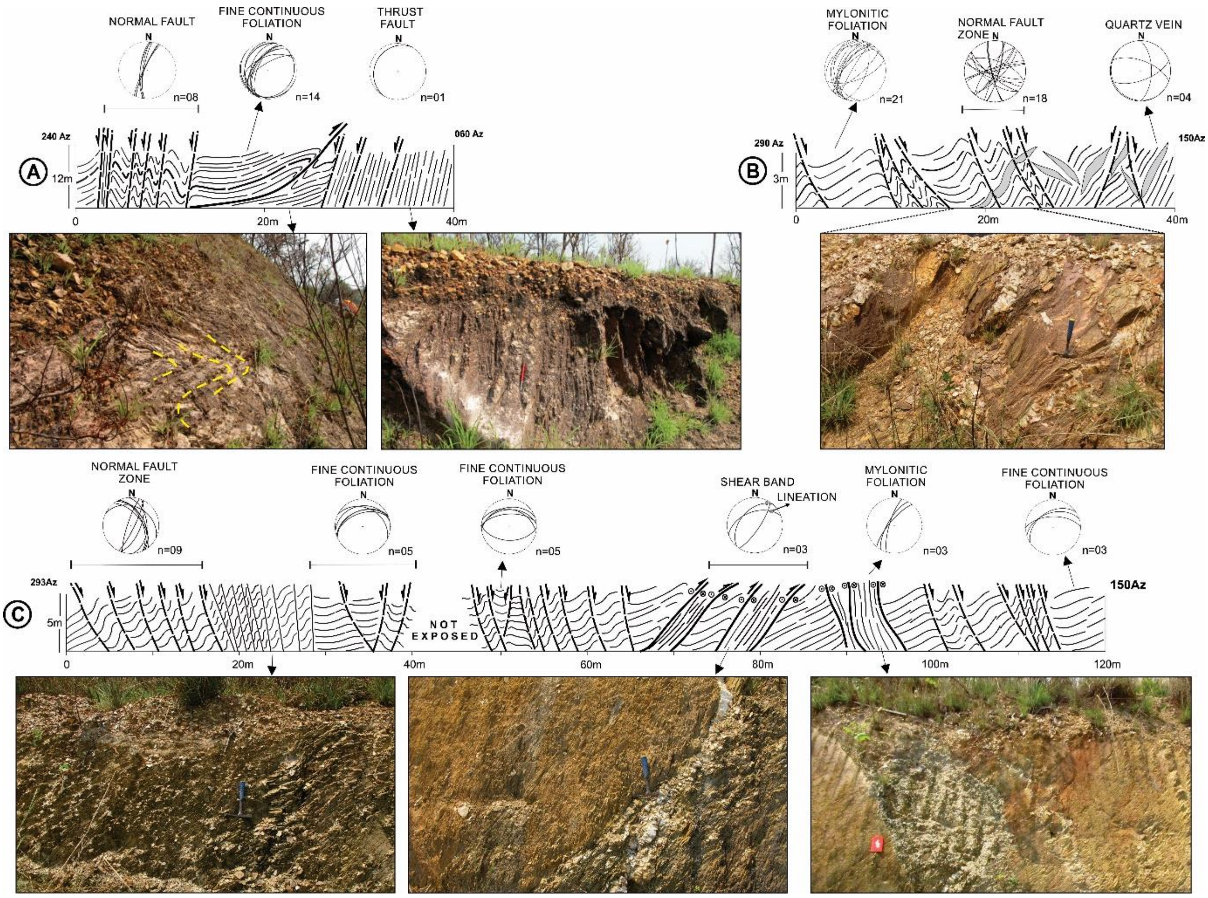

NORMAL FAULT
n=08
FINE CONTINUOUS FOLIATION
n=14
THRUST FAULT
n=01
240 Az
060 Az
A
12m
0
20m
40m
MYLONITIC FOLIATION
n=21
NORMAL FAULT ZONE
n=18
QUARTZ VEIN
n=04
290 Az
150Az
B
3m
0
20m
40m
NORMAL FAULT ZONE
n=09
FINE CONTINUOUS FOLIATION
n=05
FINE CONTINUOUS FOLIATION
n=05
SHEAR BAND
LINEATION
n=03
MYLONITIC FOLIATION
n=03
FINE CONTINUOUS FOLIATION
n=03
293Az
150Az
C
5m
NOT EXPOSED
0
20m
40m
60m
80m
100m
120m

Fig. 6.

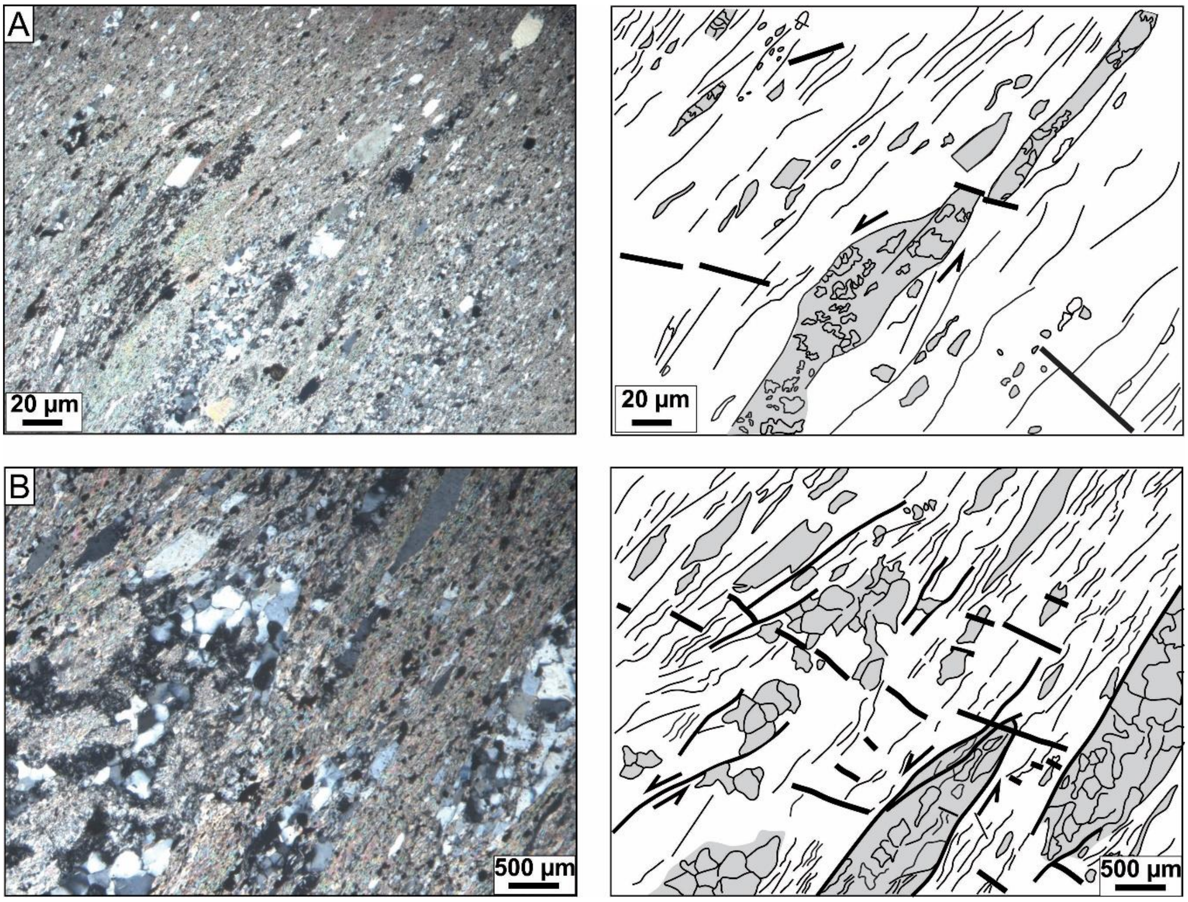


Fig. 7.

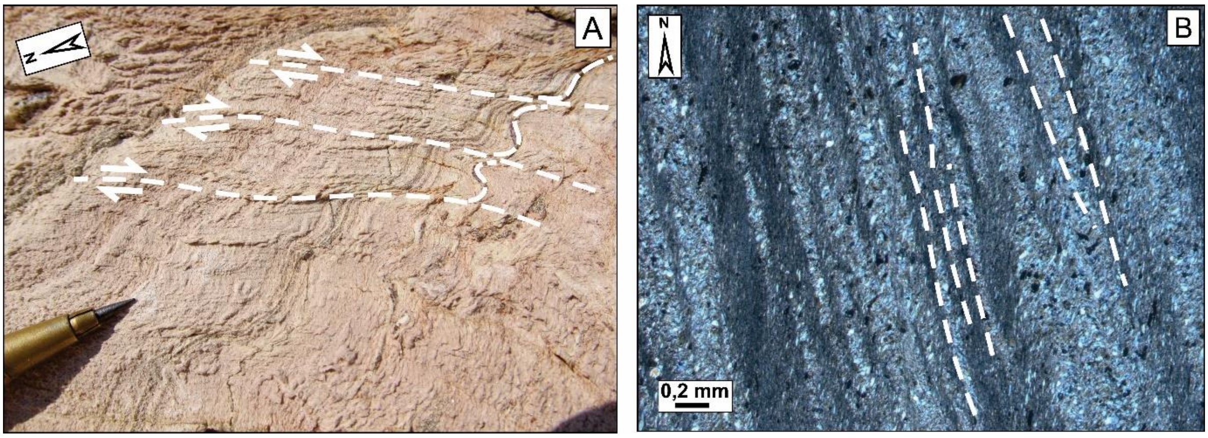


Fig. 8.

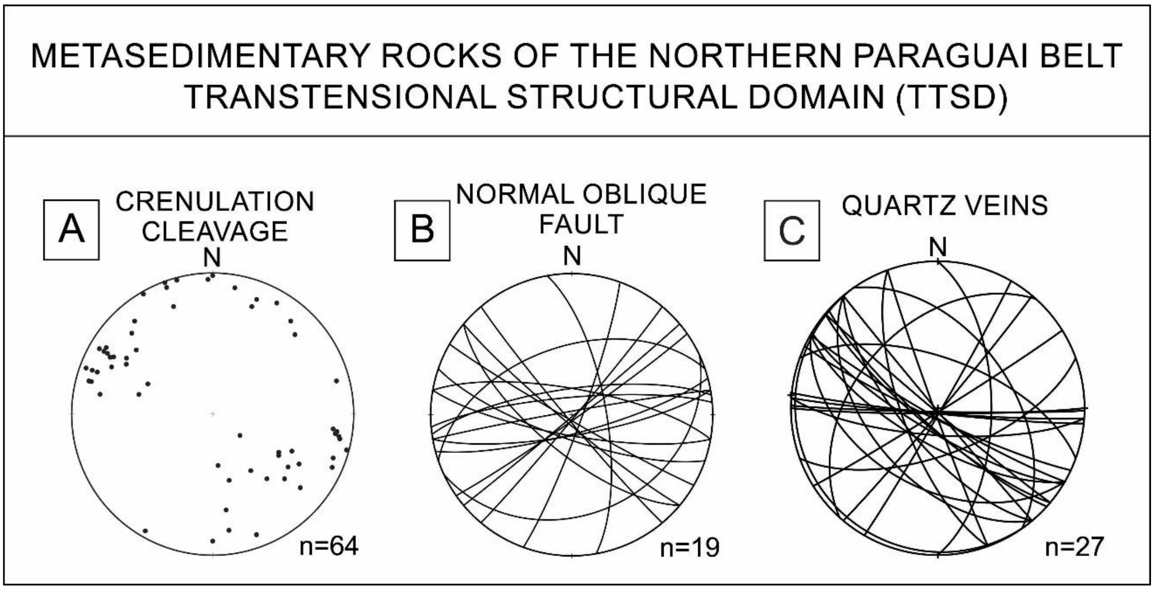

METASEDIMENTARY ROCKS OF THE NORTHERN PARAGUAI BELT
TRANSTENSIONAL STRUCTURAL DOMAIN (TTSD)
A
CRENULATION CLEAVAGE
N
n=64
B
NORMAL OBLIQUE FAULT
N
n=19
C
QUARTZ VEINS
N
n=27

Fig. 9.

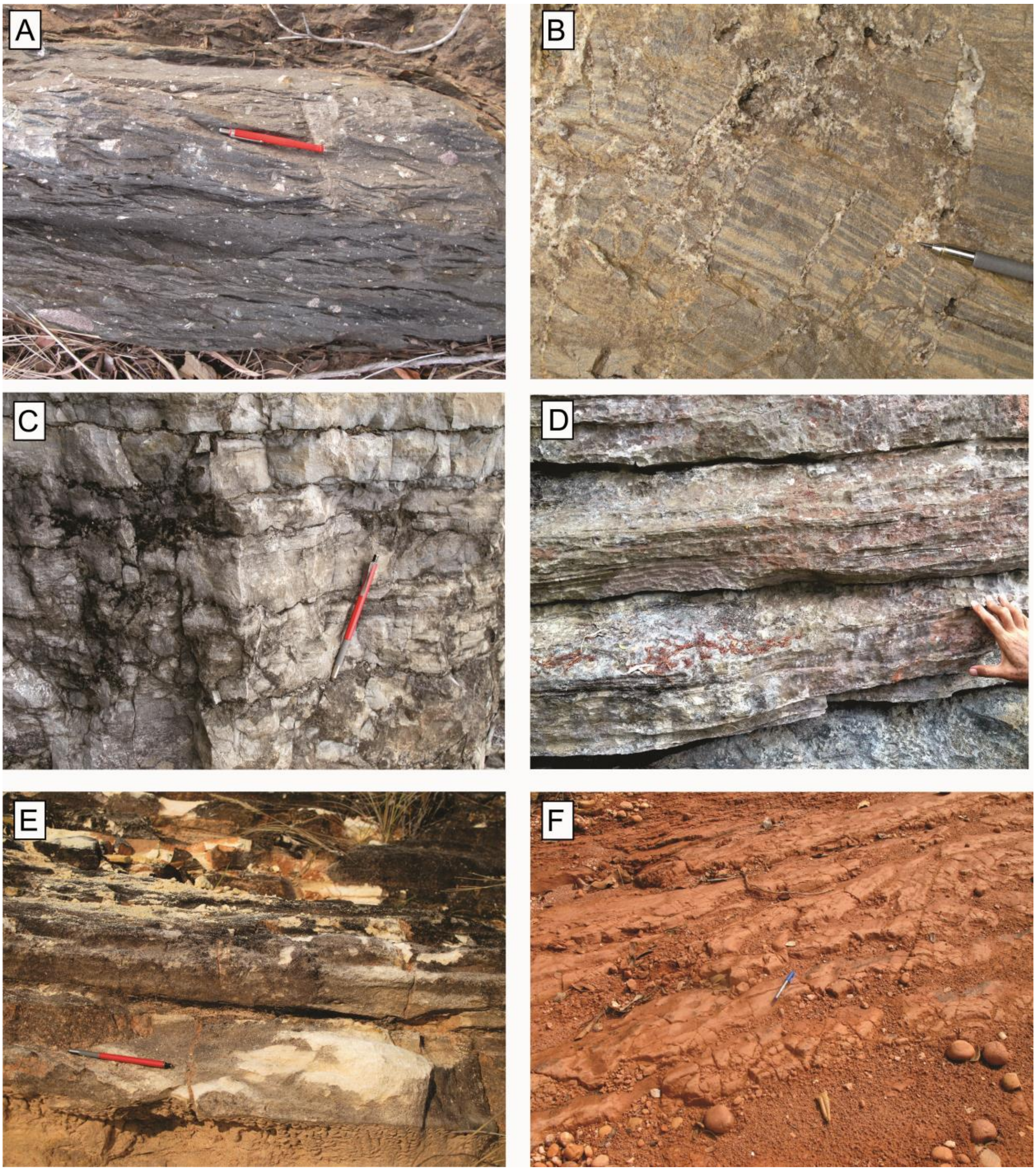


Fig. 10.

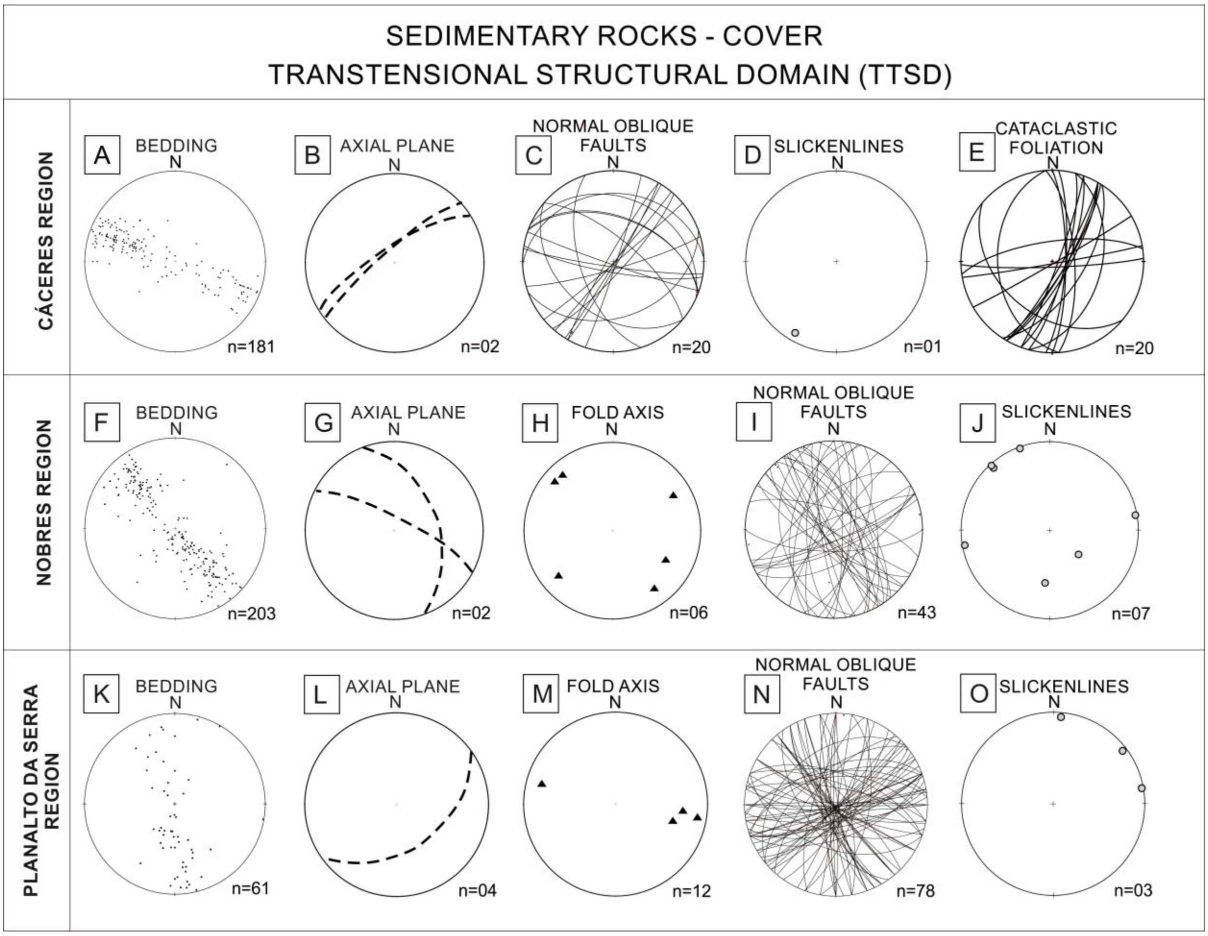
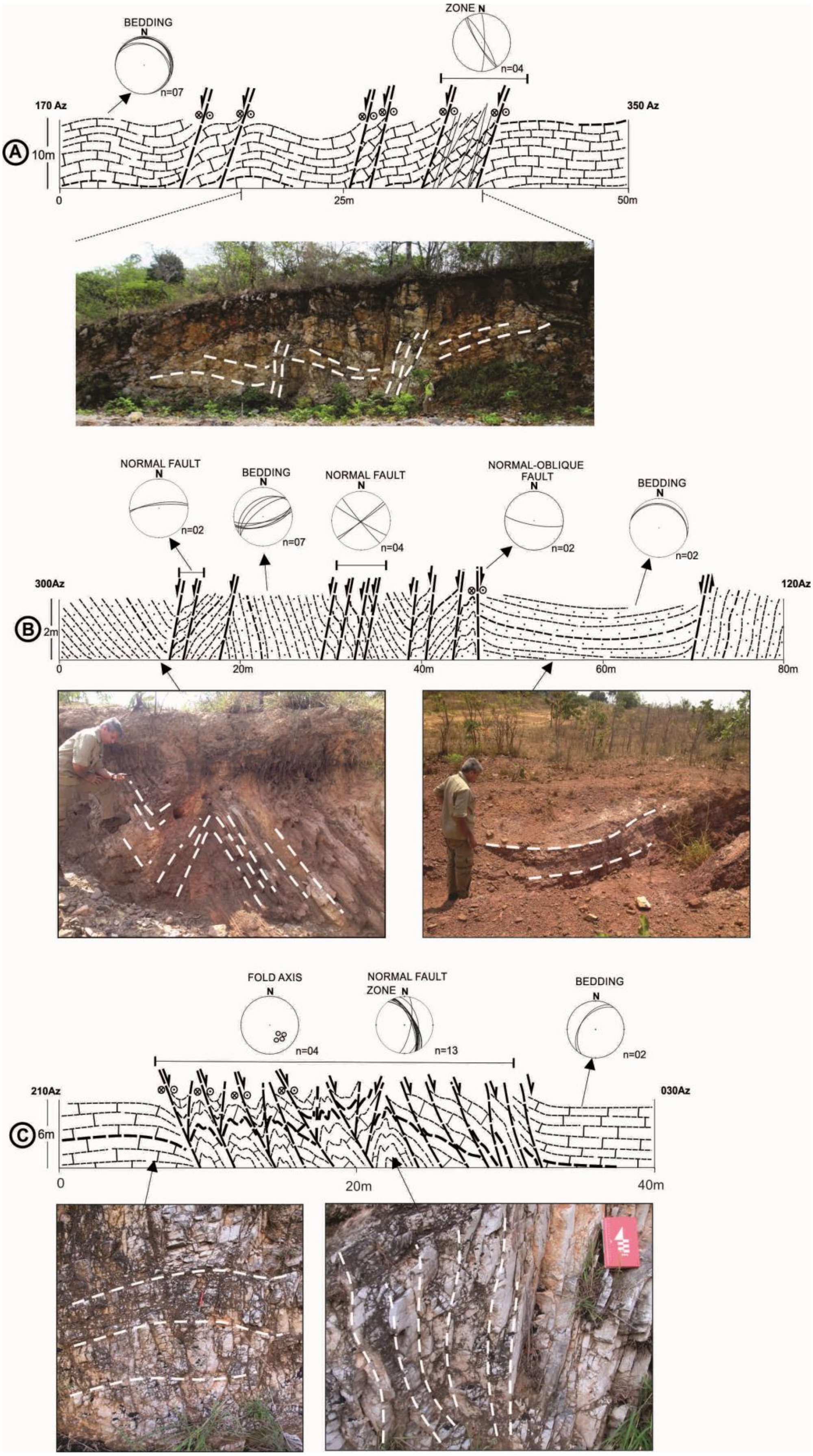

SEDIMENTARY ROCKS - COVER
TRANSTENSIONAL STRUCTURAL DOMAIN (TTSD)
CÁCERES REGION
A BEDDING N n=181
B AXIAL PLANE N n=02
C NORMAL OBLIQUE FAULTS N n=20
D SLICKENLINES N n=01
E CATACLASTIC FOLIATION N n=20
NOBRES REGION
F BEDDING N n=203
G AXIAL PLANE N n=02
H FOLD AXIS N n=06
I NORMAL OBLIQUE FAULTS N n=43
J SLICKENLINES N n=07
PLANALTO DA SERRA REGION
K BEDDING N n=61
L AXIAL PLANE N n=04
M FOLD AXIS N n=12
N NORMAL OBLIQUE FAULTS N n=78
O SLICKENLINES N n=03

Fig. 11.



BEDDING
N
n=07
ZONE N
n=04
170 Az
350 Az
A
10m
0
25m
50m
NORMAL FAULT
N
n=02
BEDDING
N
n=07
NORMAL FAULT
N
n=04
NORMAL-OBLIQUE FAULT
N
n=02
BEDDING
N
n=02
300Az
120Az
B
2m
0
20m
40m
60m
80m
FOLD AXIS
N
n=04
NORMAL FAULT ZONE
N
n=13
BEDDING
N
n=02
210Az
030Az
C
6m
0
20m
40m

Fig. 12.

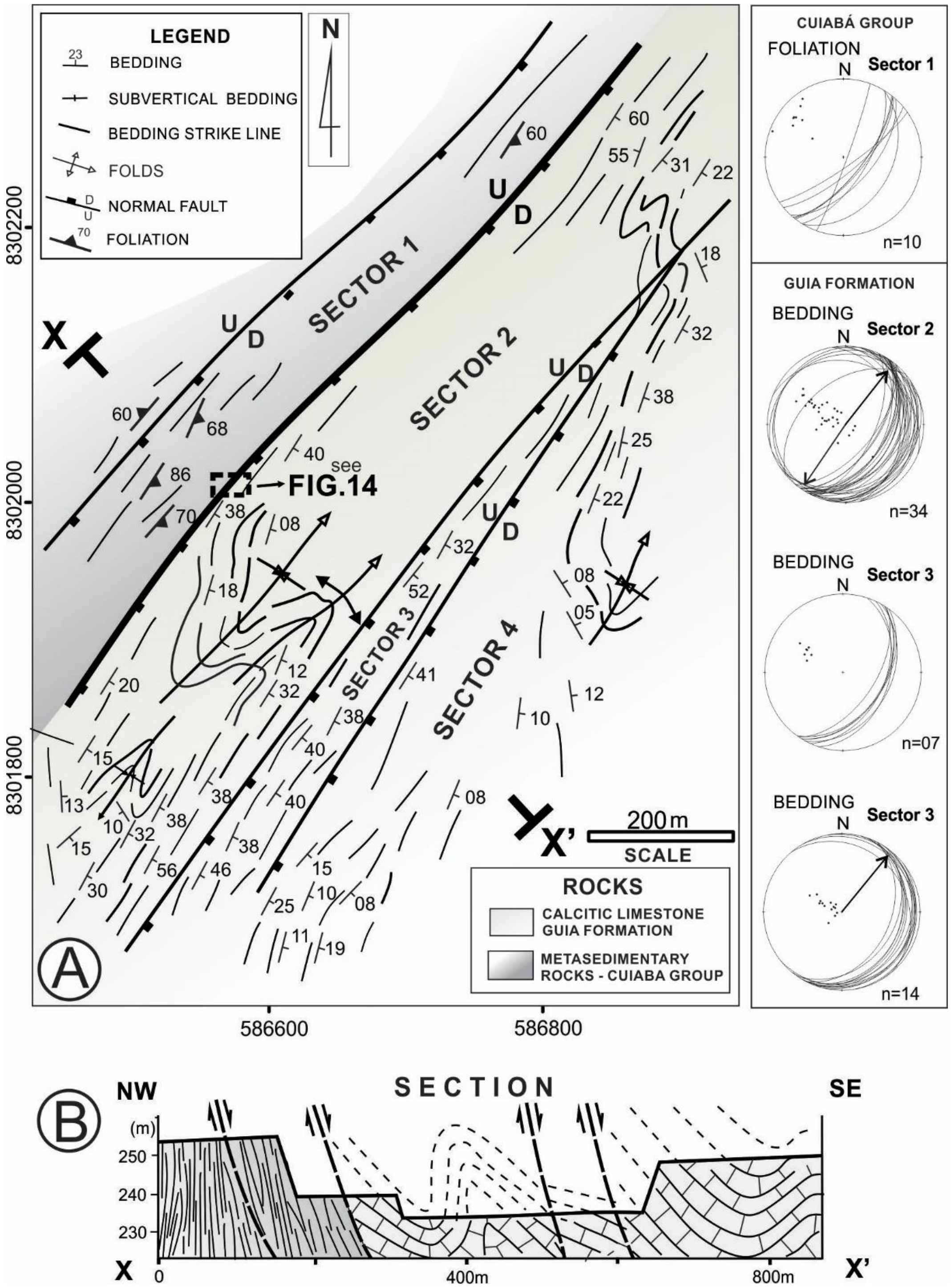
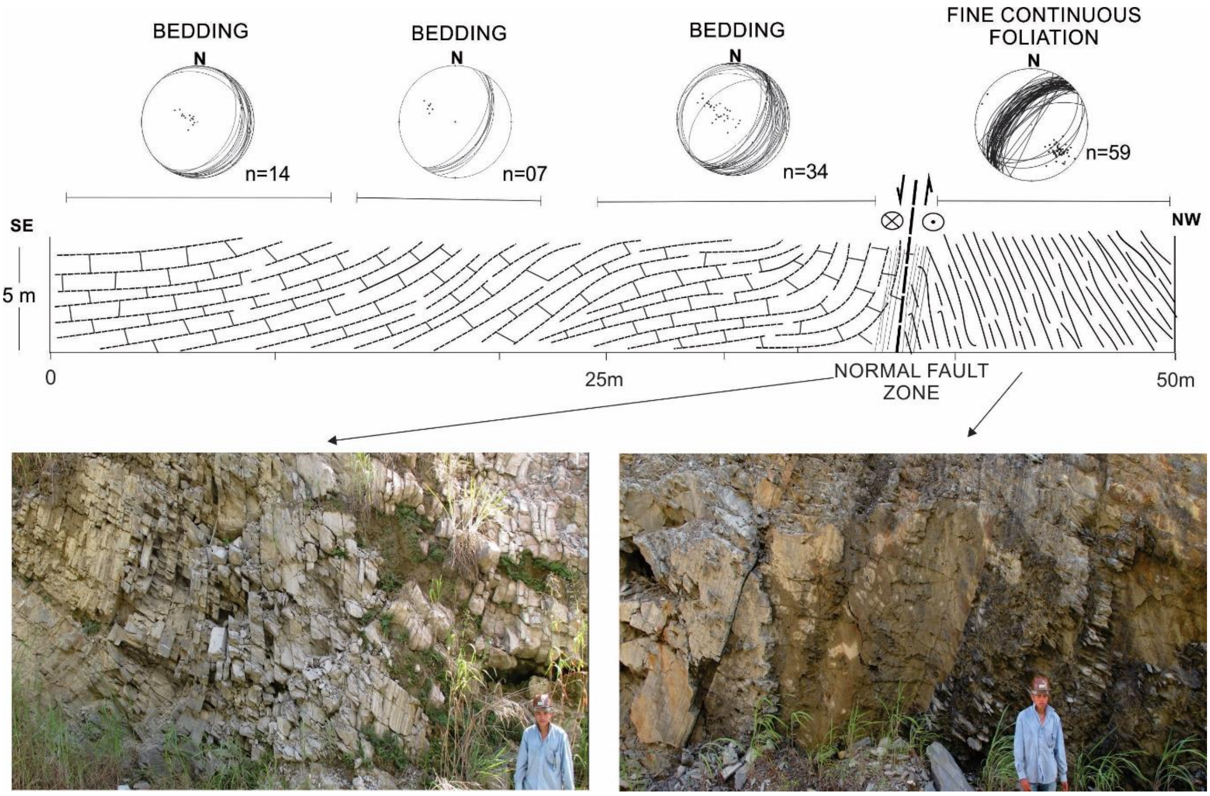

LEGEND
BEDDING
SUBVERTICAL BEDDING
BEDDING STRIKE LINE
FOLDS
NORMAL FAULT
FOLIATION
N
SECTOR 1
SECTOR 2
SECTOR 3
SECTOR 4
see FIG.14
X
X'
200 m
SCALE
ROCKS
CALCITIC LIMESTONE GUIA FORMATION
METASEDIMENTARY ROCKS - CUIABA GROUP
8302200
8302000
8301800
586600
586800
CUIABÁ GROUP
FOLIATION
Sector 1
n=10
GUIA FORMATION
BEDDING
Sector 2
n=34
BEDDING
Sector 3
n=07
BEDDING
Sector 3
n=14
A
B
SECTION
NW
SE
(m)
250
240
230
0
400m
800m

Fig. 13.

27 
BEDDING
N
n=14
BEDDING
N
n=07
BEDDING
N
n=34
FINE CONTINUOUS FOLIATION
N
n=59
SE
NW
5 m
0
25m
50m
NORMAL FAULT ZONE

28 Fig. 14.

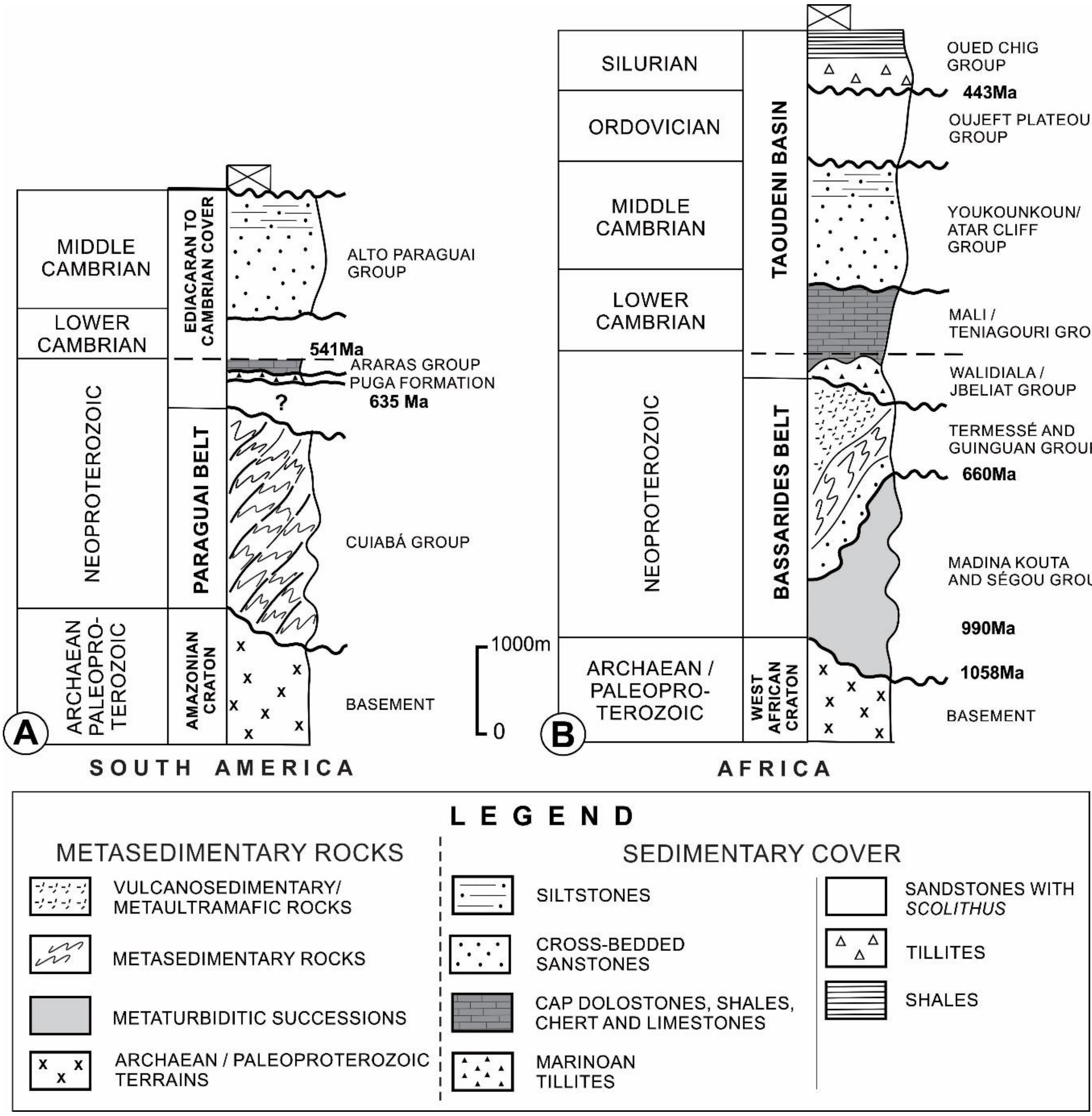

MIDDLE CAMBRIAN
LOWER CAMBRIAN
NEOPROTEROZOIC
ARCHAEAN PALEOPRO-TEROZOIC
EDIACARAN TO CAMBRIAN COVER
PARAGUAI BELT
AMAZONIAN CRATON
ALTO PARAGUAI GROUP
541Ma
ARARAS GROUP
PUGA FORMATION
635 Ma
?
CUIABÁ GROUP
BASEMENT
A
SOUTH AMERICA
1000m
0
SILURIAN
ORDOVICIAN
MIDDLE CAMBRIAN
LOWER CAMBRIAN
NEOPROTEROZOIC
ARCHAEAN / PALEOPRO-TEROZOIC
TAOUDENI BASIN
BASSARIDES BELT
WEST AFRICAN CRATON
OUED CHIG GROUP
443Ma
OUJEFT PLATEOU GROUP
YOUKOUNKOUN/ ATAR CLIFF GROUP
MALI / TENIAGOURI GROUP
WALIDIALA / JBELIAT GROUP
TERMESSÉ AND GUINGUAN GROUP
660Ma
MADINA KOUTA AND SÉGOU GROUP
990Ma
1058Ma
BASEMENT
B
AFRICA
LEGEND
METASEDIMENTARY ROCKS
VULCANOSEDIMENTARY/ METAULTRAMAFIC ROCKS
METASEDIMENTARY ROCKS
METATURBIDITIC SUCCESSIONS
ARCHAEAN / PALEOPROTEROZOIC TERRAINS
SEDIMENTARY COVER
SILTSTONES
CROSS-BEDDED SANSTONES
CAP DOLOSTONES, SHALES, CHERT AND LIMESTONES
MARINOAN TILLITES
SANDSTONES WITH SCOLITHUS
TILLITES
SHALES

Fig. 15.

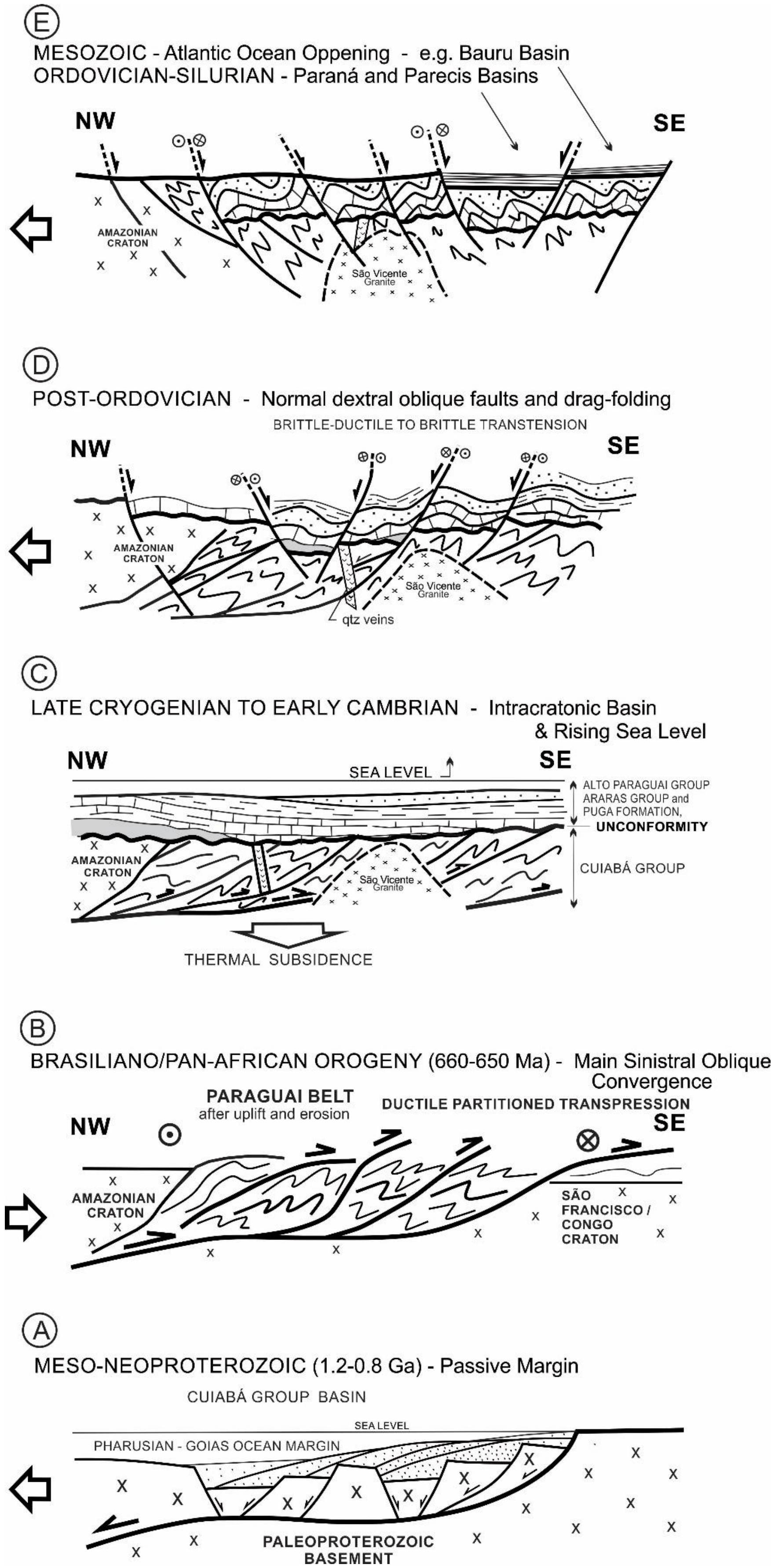

E
MESOZOIC - Atlantic Ocean Oppening - e.g. Bauru Basin
ORDOVICIAN-SILURIAN - Paraná and Parecis Basins
NW
SE
AMAZONIAN CRATON
São Vicente Granite
D
POST-ORDOVICIAN - Normal dextral oblique faults and drag-folding
BRITTLE-DUCTILE TO BRITTLE TRANSTENSION
NW
SE
AMAZONIAN CRATON
São Vicente Granite
qtz veins
C
LATE CRYOGENIAN TO EARLY CAMBRIAN - Intracratonic Basin & Rising Sea Level
NW
SE
SEA LEVEL
ALTO PARAGUAI GROUP
ARARAS GROUP and
PUGA FORMATION,
UNCONFORMITY
AMAZONIAN CRATON
São Vicente Granite
CUIABÁ GROUP
THERMAL SUBSIDENCE
B
BRASILIANO/PAN-AFRICAN OROGENY (660-650 Ma) - Main Sinistral Oblique Convergence
PARAGUAI BELT
after uplift and erosion
DUCTILE PARTITIONED TRANSPRESSION
NW
SE
AMAZONIAN CRATON
SÃO FRANCISCO / CONGO CRATON
A
MESO-NEOPROTEROZOIC (1.2-0.8 Ga) - Passive Margin
CUIABÁ GROUP BASIN
SEA LEVEL
PHARUSIAN - GOIAS OCEAN MARGIN
PALEOPROTEROZOIC BASEMENT

Fig. 16.